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Fuel conditions and fire behavior characteristics of
managed *Picea abies* and *Pinus sylvestris* forests
in Finland

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Academic dissertation

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ABSTRACT

The objectives of this study were to quantify and qualify the impact of structural stand characteristics on ignition potential, surface fuel moisture, and fire behavior in *Pinus sylvestris* L. and *Picea abies* (L.) Karst stands and to test the applicability of the Canadian Fire Weather Index System and the Finnish Fire Risk index for the modeling of stand type –specific fire danger in Finland. Additionally, the study analyzes the seasonal patterns of fire activity and the relationship between observed fire activity and fire weather indices at different stages of growing season.

Field experiments on ignition potential, fuel moisture, and fire behavior were carried out in *Pinus sylvestris* or *Picea abies* dominated stands ranging 0–60 years in age during fire seasons 2001 and 2002. The field observations were analyzed in relation to stand structure and the outputs of the fire weather index systems. The relationship between fire activity and fire weather indices was studied based on national fire statistics 1996–2003, effective temperature sum, the Canadian Fire Weather Index System, and the Finnish Fire Risk Index.

Clear differences were found in the development of fire danger between open and closed stands and between closed *Picea abies* and *Pinus sylvestris* stands. Point fire ignition potential was highest in *Pinus* clear-cuts and nearly non-existing in closed *Picea* stands. Moss-dominated surface fuels were driest in clear-cut and sapling stage stands and presented the highest moisture content under closed *Picea* canopy. *Pinus sylvestris* stands carried fire under a wide range of fire weather conditions within which *Picea abies* stands consistently failed to sustain surface fire. In the national fire statistics, the daily number of reported ignitions presented three seasonal peaks, whereas the daily area burned had its most substantial peak during early summer and a smaller one very late in the season. The Finnish Fire Risk Index and The Canadian Fire Weather Index were mostly capable of explaining ignition potential and fuel moisture but unable to explain fire behavior in the experimental fires. The fire weather indices correlated with fire activity fairly well during the mid-part growing season; before and after the most active period of growing season fire activity was to a larger extent disconnected from fire danger levels indicated by the indices.

In conclusion, the development of fire danger under the same general weather conditions varied significantly between the fuel types defined by dominant tree species and stand age. Furthermore, the stage of the growing season influenced fire danger and the ability of the fire weather indices to assess the burning conditions. The modification of the general fire weather indices into stand-specific fire danger assessment tools would facilitate fire use and fire suppression operations.

Keywords: Fire weather, stand structure, ignition potential, surface fuel moisture, seasonality of fires

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LIST OF ORIGINAL ARTICLES

This doctoral thesis is based on following articles which are referred to by their Roman numerals:

- I. Tanskanen, H., Venäläinen, A., Puttonen, P., and Granström, A. 2005. Impact of stand structure on surface fire ignition potential in *Picea abies* and *Pinus sylvestris* forests in southern Finland. Canadian Journal of Forest Research 35(2): 410-420.
- II. Tanskanen, H., Granström, A., Venäläinen, A., and Puttonen, P. 2006. Moisture dynamics of moss-dominated surface fuel in relation to the structure of *Picea abies* and *Pinus sylvestris* stands. Forest Ecology and Management 226: 189-198.
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Tanskanen was responsible for all stages of the research process (planning, collection of field data, analysis, and publishing) of studies I-III, and the analysis plan, data processing, and publishing of study IV.

Granström participated in planning, data processing, and publishing of studies I-III.

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Puttonen participated in initiating, planning, and publishing of studies I-III.

Venäläinen participated in data processing and publishing studies I and II, was responsible for initiating study IV and participated in all stages of research process of study IV.

TABLE OF CONTENTS

ABSTRACT	3
ACKNOWLEDGEMENTS	4
LIST OF ORIGINAL ARTICLES	6
TABLE OF CONTENTS	7
TERMINOLOGY	8
 1 INTRODUCTION	 11
1.1 Motivation of the study	11
1.2 Fire danger – the product of fire environment	11
1.2.1 Component 1: Fuel	11
1.2.2 Component 2: Weather	13
1.2.3 Component 3: Topography	13
1.3 Quantification of fire behavior	14
1.4 Methods to assess and predict fire danger	14
1.5 General characteristics of fire environment and fires in Finland	15
1.5.1 Fuels	15
1.5.2 Climate and weather	16
1.5.3 Topography	16
1.5.4 Fire regimes	17
1.5.5 Topical issues around forest fires	17
1.6 Aims of the study	18
 2 MATERIAL AND METHODS	 18
2.1 Establishment of sample plots for studies I-III	18
2.2 The development of ignition potential (I)	20
2.3 Moisture content variation in moss-dominated surface fuels (II)	23
2.4 Fire behavior (III)	24
2.5 Seasonality of fires (IV)	27
 3 RESULTS AND DISCUSSION.....	 29
3.1 Ignition potential (I) and surface fuel moisture (II) in different stand structures	29
3.2 Fire behavior in relation to stand structure, wind, and fuel moisture (III).....	31
3.3 Seasonality of fires (I, II, IV)	34
3.4 Applicability of fire weather indices (I, II, III, IV)	35
3.5 Fire danger characteristics of managed <i>Pinus sylvestris</i> and <i>Picea abies</i> stands	38
 4 CONCLUSIONS	 40
 REFERENCES	 41
 APPENDIX 1. Description of fuel and fire behavior characteristics for different fuel types	

TERMINOLOGY

Available fuel load: The quantity of fuel that will burn under given conditions, as determined by fuel moisture content.

Curing: Drying and browning of live herbaceous vegetation.

Dead fuel: Fuel in which moisture content is governed almost entirely by atmospheric moisture (relative humidity and precipitation), air temperature, and solar radiation. Usually material with no living tissue, such as plant litter and downed woody material with the exception of live mosses.

Drip torch: Hand-held device for igniting fires by dripping flaming liquid fuel (generally a mixture of diesel and gasoline) on the materials to be burned.

Fine fuel: Fast-drying fuels of small dimensions generally having a high surface area-to-volume ratio. These fuels get ignited easily and burn readily and are usually the main medium for fire spread.

Fire behavior: The manner in which fire reacts to the influences of fuel, weather, and topography.

Fire danger: A general term used to express an assessment of both fixed and variable factors of the fire environment that determine the ease of ignition, rate of spread, difficulty of control, and fire impact

Fireline intensity (Byram's): The rate of heat energy release per unit time per unit length of flaming front (kW m^{-1}). This measure was introduced by G. Byram 1959 and it is considered as the main indicator of fire effects and the difficulty of control. Byram's fireline intensity is numerically calculated as the product of the heat of combustion (kJ kg^{-1}), quantity of the fuel consumed in the flaming front (kg m^{-2}), and linear rate of fire spread (m s^{-1}).

Flame height: The vertical distance of flame tips of a fire front from the ground surface.

Flame length: The distance between the flame tip and the midpoint of the flame depth at the base of the flame (generally the ground surface).

Fuel: Combustible material; in the context of forest fires, consists of dead and live vegetation.

Fuel arrangement: The way fuel particles and fuel layers lie in relation to one another and their distribution over an area, both horizontally and vertically.

Fuel moisture content: The proportional amount of water held by fresh fuel, expressed as a percentage of the mass of water in the fresh fuel over the fuel dry-mass (measured after 24 h at 105°C).

Fuel type: An identifiable association of fuel elements of a distinctive plant species, form, size, arrangement, or other characteristics that will exhibit predictable fire behavior under specified topography and weather conditions (Merrill and Alexander 1987)

Ground/subsurface fire and fuel: Fire smoldering or glowing in the decomposing organic matter (e.g. duff, roots, or peat) below the surface fuel layer (Merrill and Alexander 1987)

Head fire: The part of fire having the fastest rate of spread, proceeding downwind or upslope (Merrill and Alexander 1987).

Heavy/coarse fuel: Large diameter woody fuel, such as logs, or deep organic material (Merrill and Alexander 1987). Can burn only after a long period of drying and preheating and then contribute to fire intensity.

Live fuel: Living plants (trees, shrubs etc.) in which the seasonal moisture content cycle is controlled largely by internal physiological mechanisms and phenology rather than by external weather.

Relative humidity: The proportion (%) that the amount of moisture contained by a parcel of air fills of the maximum moisture holding capacity the air parcel has at prevailing air temperature.

Rate of spread: The speed at which a fire extends itself on a horizontal plane (m min^{-1} , m h^{-1}).

Surface-area-to-volume ratio: Ratio of the area of the surface of a fuel particle to its volume; the higher the ratio, the finer the particle (McPherson et al. 1990).

Surface fire / fuel: Fire burning near or at forest floor surface consuming moss, fine litter, dwarf shrubs, or slash.

Torching: The ignition and flare-up of a tree or small group or trees, often from bottom to top.

Total fuel load: The dry weight of all combustible material (phytobiomass) per unit area (kg m^{-2} or metric tons ha^{-1})

1 INTRODUCTION

1.1 Motivation of the study

Despite of the acknowledged ecological role of fire in *Pinus sylvestris* L. and *Picea abies* L. Karst dominated boreal forests (Wein and MacLean 1983, Engelmark 1987, Goldammer and Furyaev 1996, Esseen et al. 1997) there have been no systematic empirical studies on fuel conditions and fire behavior in Finland. As a result, the semi-natural *Pinus sylvestris* and *Picea abies* forests which dominate Finnish landscape currently lack even the very basic fire danger descriptions which leads to inefficient use of resources in fire surveillance, detection, and suppression and complicates the implementation of controlled burning, recommended for biodiversity reasons (Granström 2001, Kuuluvainen et al. 2002). Empirical studies on fuel moisture, ignition potential, and fire behavior are necessary prerequisites for the assessment of fire danger, prediction of fire effects, and for developing fire management tools (Albini 1976). This study will examine fire danger characteristics of managed forest structures now dominating Finnish landscape aiming to provide a starting point for stand structure -based fire danger assessment system.

1.2 Fire danger – the product of fire environment

Forest fire danger as a term refers to an assessment of fixed and variable factors of the fire environment and their influences on the ease of ignition, rate of spread, difficulty of control and fire impact (Merrill and Alexander 1987). Fire environment is considered to consist of three main components: fuel, weather, and topography (Countryman 1972, Rothermel 1972). Additionally, fire danger is affected by the interaction of the components with each other and the fire itself (Countryman 1972, Rothermel 1972).

Fire behavior and fire danger are usually described in association with a fuel model or fuel type (e.g. Alexander et al. 1991, Hirsch 1996). A fuel model is a set of a measurable fuel bed properties, quantified for a distinctive vegetation community, that can be used as input for mathematical fire spread or fire effect model (Rothermel 1972, Scott and Burgan 2005). Fuel type has been defined as an identifiable association of fuel elements of a distinctive plant species, form, size, arrangement, or other characteristics that will exhibit predictable fire behavior under specified topography and weather conditions (Merrill and Alexander 1987). Fuel types and fuel models are often given names which indicate their key species e.g. Black Spruce-Lichen Woodland (Alexander et al. 1991) or structural characteristics e.g. Moderate Load, Dry Climate Grass (Scott and Burgan 2005).

1.2.1 Fire environment: fuel

Fuel, together with oxygen and initial heat, is a critical element needed for the occurrence of flaming combustion (Byram 1959) (Fig. 1). Further on, the physical and chemical characteristics of fuel determine the ease of ignition (i.e. how much preheating time is needed for ignition, which subsequently defines the rate of fire growth), the intensity of burning reaction, and finally the impact of fire on the ecosystem (Rothermel 1972, Pyne et al. 1996) (Fig. 1). Therefore, Characterization of fuels is a core component of

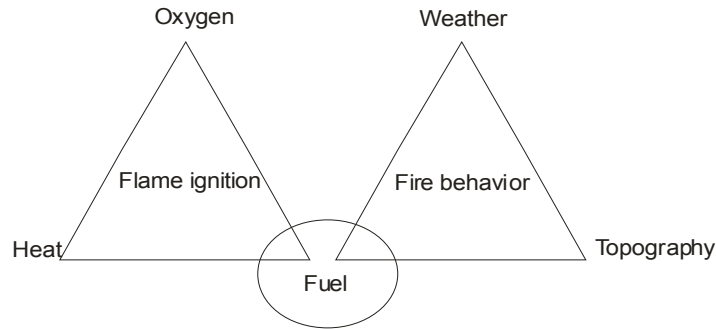


Figure 1. Fuel is one of the three prerequisites for ignition (Byram 1959) and one of the three main components of fire environment that modify fire behavior (Countryman 1972).

fire danger studies (e.g. McRae et al. 1979, Pyne et al. 1996).

Wildland fuels can be classified into ground (or below-surface), surface, and crown fuels according to the layer where they are located (Chandler et al. 1983, Pyne et al. 1996, Nelson 2001). Ground fuels may contribute to the intensity of a surface fire or support glowing combustion (Pyne et al. 1996). Surface fuels are of great importance to fire danger assessment because this is the layer where flaming combustion usually gets started and spreads (Pyne et al. 1996). Crown fuel layer does not always participate in combustion process but when doing so substantially increases fire intensity and fire spread rates (Alexander 1982, Viegas 1998b).

The quantity of fuel is a basic variable in the assessment of fire danger (McRae et al. 1979). Total fuel load roughly equals the total live and dead plant biomass present on a site and is primarily determined by the growth of plants and decomposition rates of the dead organic material (Chandler et al. 1983). Forest fire, however, never consumes all organic material but a proportion of it called available fuel (Chandler et al. 1983, Pyne et al. 1996). The amount of the available fuel on a certain site varies on a daily and weekly basis, because it is determined primarily by an unstable component: weather and its impact on fuel moisture content (Pyne et al. 1996). Fuel moisture is a crucial factor that modifies all essential fire danger parameters such as ease of ignition, fire spread rate, and fire intensity (Fosberg et al. 1970, Rothermel 1972, Nelson 2001). Moisture content in forest fire sciences is usually expressed as a percentage of the mass of water held by a unit mass of oven-dry fuel (Pyne et al. 1996).

The way fuel moisture responds to changing weather conditions depends on the dimensions, arrangement, physical structure, and dead/live-ratio of the fuel material (Nelson 2001). A commonly used, dimension-based classification separates wildland fuel material into fine, medium, and heavy fuels (Van Wagner 1987, Viegas 1998b). Fine dead fuels primarily consist of fine litter particles such as needles, leaves and twigs, or the exposed uppermost layer of organic forest floor (Van Wagner 1987). Fine dead fuels have a small water holding capacity and dry out quickly (Van Wagner 1982, 1987). Due to their rapid drying process, fine fuels most often fall in the category of available fuel and are the main contributor to fire ignition potential and spread rate (Viegas 1998b). Medium fuels are formed by more robust litter and organic layer below the exposed surface (Viegas 1998b). Heavy fuels consist of downed or standing logs (Viegas 1998b) or organic layers located deep below the surface fuel layer and require weeks or months of dry weather before they will be dry enough to burn (Chandler et al. 1983). Participation of medium and heavy fuels

mainly increases fireline intensity, prolongs the residence time of flaming combustion, and increases the severity of fire impacts (Ryan 2002).

Fuel arrangement observes the horizontal and vertical distribution of material within a fuel complex and can be described by continuity and spacing between fuel layers and individual fuel particles (Pyne et al. 1996). Compactness and surface-area-to-volume ratio are important physical characteristics that modify the moisture dynamics, ignition process, and combustibility of fuels (Brown 1970, Burgan and Rothermel 1984).

Whether fuel consists of dead organic material or live plants affects its average moisture content conditions and how fast moisture content changes (Pyne et al. 1996, Nelson 2001). In dead fuels, moisture is primarily controlled by physical fuel properties and air temperature, relative humidity, precipitation, and wind speed (Fosberg et al. 1970, Van Wagner 1979, 1982, Nelson 2001). In live fuels, moisture dynamics principally are a seasonal process i.e. mostly unresponsive to hourly or daily weather changes but presenting a different setting based on seasonal vegetation development or long-term weather patterns (Chrosiewicz 1986, Pyne et al. 1996). Live fuels typically present steady, fairly high moisture contents and may often act as fire retardants (Pyne et al. 1996).

1.2.2 Fire environment: weather

Weather modifies fuel composition through plant growth and decomposition (Chandler et al. 1983), is the main driver of fuel moisture processes (Pyne et al. 1996, Nelson 2001), ignites fires by lightning (Gromtsev 2002), and can directly accelerate and steer fire spread through wind (e.g. Anderson and Rothermel 1965, Rothermel 1972). The most influential weather variables in terms of fuel moisture, ignition potential, and fire behavior are relative humidity, air temperature, precipitation, and wind speed (Fosberg et al. 1970, Van Wagner 1979, 1982, Nelson 2001). Changes in these weather factors have immediate impact on fine dead fuel moisture content and delayed influence on heavier dead fuels (Van Wagner and Pickett 1985, Van Wagner 1987). Relative humidity is the most important direct factor that controls fine dead fuel drying because it defines the capacity of the air surrounding fuel particles to absorb excess moisture (Fosberg et al. 1970). Main processes that can change the relative humidity status of the air are solar radiation and ventilation of the fuel-air interface (Kunkel 2001). Energy received from solar radiation raises the temperature of the air which increases its capacity to absorb moisture (Kunkel 2001). Ventilation enhances dead fuel drying by replacing moist air next to fuel particle with drier air (Kunkel 2001). Long-term drought will eventually decrease live fuel moisture and lead to a gradual transition of fuel status from live to dead as a result of curing (Pyne et al. 1996). Wind speed and wind direction primarily determine the direction of the fastest fire spread (Rothermel 1972, Chandler et al. 1983, Pyne et al. 1996, Viegas 1998b). High wind speeds facilitate the occurrence of large fires and lead to increased difficulty in fire control (Pyne et al. 1996, Viegas 1998b).

1.2.3 Fire environment: topography

Topographic features, such as elevation, slope, and aspect, create variation in local weather conditions which then translates into spatial variation in the composition and moisture content of fuels (Countryman 1972, Pyne et al. 1996). Slope angle directly affects the rate of fire spread by enhancing (up-slope) or reducing (down-slope) heat transfer from the flaming front to unburned fuel (Rothermel 1972). Local slope and aspect variation causes

differential surface heating which through the occurrence of local convective winds may result in abrupt changes in the spread direction and intensity of fire (Schroeder and Buck 1970). Combining the various direct and indirect impacts of topographic features on fires, it becomes obvious that the higher the spatial topographic variation, the more difficult it is to predict how fire will behave (Viegas 1998a).

Topographic variation may also include features that prevent or slow down fire spread (Pyne et al. 1996). These fire barriers may be natural, such as bare rocks, lakes, streams, and less flammable vegetation types or human-made, e.g. roads and cultivations (Pyne et al. 1996).

1.3 Quantification of fire behavior

Fire behavior refers to the dynamics of a fire event, i.e. how a fire burns and moves as a response to the modifying forces of its surroundings. In wildfires that present flaming combustion, visible flames are the objects to observe and measure. Length, height, and tilt angle of flames, and the width, depth, and spread rate of a flaming front from one place to another are the most typical characteristics used to describe wildland fire behavior (Pyne et al. 1996). Flame length is the distance between the midpoint of the flame base at the ground surface and the flame tip (Merrill and Alexander 1987), whereas flame height is the average maximum vertical distance of the flame tip from the ground straight below it (Merrill and Alexander 1987). If a flame is burning upright (i.e. without tilt caused by wind or slope impact), flame length equals flame height. Byram's fireline intensity (Byram 1959) is a fire behavior variable developed to describe the power of the combustion reaction. Fireline intensity estimates the heat release from flaming zone per unit length of fire perimeter per unit time (kW m^{-1}), and it can be calculated from the fuel consumption and rate of spread or estimated from the average flame length (Alexander 1982, Pyne et al. 1996). Flame height can be related to the lethal scorching of tree foliage or the likelihood of crowning (Pyne et al. 1996).

Fire behavior in a single fire may be spatially and temporally highly variable due to complex interconnections of fuels, weather, and topography (Pyne et al. 1996) which makes the quantification of fire danger and fire behavior a challenging task (Viegas 1998b). To simplify analysis, fire behavior is often observed in only one of the three main fuel layers (ground, surface, or crown) at a time (Van Wagner 1983, Pyne et al. 1996). Surface fires have been the focal point of fire behavior studies because most forest fires get started and spread in surface fuel layer, and crown fires in most of the cases are supported by a fire burning the surface fuels (Pyne et al. 1996).

1.4 Methods to assess and predict fire danger

Fire danger rating refers to a process where the individual and combined influences of different factors on fire danger are evaluated systematically producing qualitative and/or numerical indices that can be used as guides in fire management activities (Stocks et al. 1989). The core components of fire danger rating systems are weather-based fuel moisture models and the prediction of fire behavior as a function of fuel moisture and weather during burning (Stocks et al. 1989).

Destructive on-site fuel moisture sampling is the most accurate method for determining the fuel moisture content. Due to the time spent for collecting and drying the samples this method, however, is unable to give insight on current or future fire danger conditions. To make fuel moisture and fire behavior assessment less labor-intensive and more proactive, various models have been developed to predict fire danger based on weather conditions (Van Wagner 1987, Stocks et al. 1989). The Canadian Fire Weather Index System generates time series of fuel moisture index values as a function of air temperature, relative humidity, precipitation, and wind speed (Van Wagner 1987, Stocks et al. 1989). The Finnish Fire Risk Index additionally uses solar radiation for input (Heikinheimo et al. 1998, Venäläinen and Heikinheimo 2003). Fire weather indices provide general estimates of fuel moisture that exclude the variation caused by local fuel types (Nelson 2001) and boundary layer weather conditions (Fosberg et al. 1970, Oke 1987, Kunkel 2001). The Canadian Forest Fire Danger Rating System (Van Wagner 1987, Stocks et al. 1989), to which the FWI belongs, contains indices that estimate fire behavior characteristics, such as the rate of spread and fireline intensity (Van Wagner 1987, Stocks et al. 1989). Other systems used for large-area fire danger prediction are the National Fire Danger Rating System (Deeming et al. 1978) used in the USA and McArthur's Forest Fire Danger Meters (McArthur 1967, Noble et al. 1980) applied in Australia.

Modeling fire behavior taking into account the spatial and temporal variation of fuel, topography, and weather used to be a demanding task. Lately, the rapid evolvement of GIS and computing technology have enabled spatial fire growth simulations (Finney 1998, Richards 2000) that combine information of topography, fuel types, and weather and produce predictions of fire behavior and extent of burned area at various spatial and temporal scales.

1.5 General characteristics of fire environment and fires in Finland

1.5.1 Fuels

The southern boreal forest landscape in Finland is dominated by coniferous forest fuel types. Approximately 86% of the land area is covered by forest, and nearly 57% of the forest land area is dominated by *Pinus sylvestris* (Scots pine) and 32% by *Picea abies* (Norway spruce) (Finnish Forest Research Institute 2000). As their understory, *Pinus sylvestris* and *Picea abies* stands typically have a low, 10-30 cm high, layer of sparsely distributed ericaceous dwarf shrubs. Among the common shrubs, *Vaccinium myrtillus* L. is considered a characteristic species for *Picea abies* dominated sites and *V. vitis-idaea* L. for *Pinus sylvestris* sites (Cajander 1926). The surface fuel layer consists of live forest moss carpet mixed with a minor amount of litter (Van Wagner 1983, Schimmel and Granström 1997). Under the live moss, forest floor contains other organic fuel layers, such as decomposing dead moss, plant residues, and downed woody material of varying depth (Van Wagner 1983).

Live moss layer is dominated by feather moss species; especially *Pleurozium schreberi* (Brid.) Mitt. which alone covers on average up to 50% of the forest floor (Mäkipää 2000). Boreal forest mosses are structurally considered fine fuels (Schimmel and Granström 1997). They have high surface-to-volume ratios of 115-135 cm⁻¹ which makes them very flammable (Brown 1970, Norum 1982, Schimmel and Granström 1997) and sensitive to changes in atmospheric conditions. Boreal forest mosses present features from both live and

dead fuel moisture dynamics. Mosses are capable of storing very high amounts of water; up to 500-600% on dry-weight basis (Dilks and Proctor 1979, Granström and Schimmel 1998). Mosses are, however, also mostly unable to control their water content which causes them to lose moisture rapidly under dry weather conditions (Proctor 1981) and reach extremely low moisture contents comparable to dead fine fuels at their driest (Norum 1982).

1.5.2 Climate and weather

Being located in the coastal zone of the Eurasian continent, Finland presents both continental and maritime climate features (http://www.fmi.fi/weather/climate_3.html, Solantie 1990). In Köppen's climate classification, Finland belongs to the temperate coniferous-mixed forest zone where the rainfall is moderate in all seasons (Solantie 1990).

Due to the far north location between the 60th and 70th latitudes, the level of solar radiation varies considerably between seasons (Solantie 1990). The yearly maximum of solar radiation is reached before summer solstice in early June (Solantie 1990). The daily maximum of solar radiation usually occurs before noon (Solantie 1990).

The mean annual temperature is 5.5°C in the warmest part of the country, the southwest of Finland (Drebs et al. 2002). The 0°C mean annual temperature limit runs through northern Finland nearby the Arctic Circle (66°33'N) (Solantie 1990). The mean daily temperature during summer, the primary fire season, is above 10°C (Drebs et al. 2002). The highest daily inland summer temperatures range 32-35°C (Drebs et al. 2002). In southern Finland, summer starts in late May and ends in mid-September; in the extreme north of the country (Lapland), summer is approximately two months shorter (Solantie 1990).

Relative humidity is on average highest (90%) in November and December and lowest (65-70%) during the early fire season in May and June (Drebs et al. 2002). The mean annual rainfall in Finland is 600-700 mm (Drebs et al. 2002). Precipitation pattern is characterized by irregular but relatively frequent rain events occurring during all seasons (Solantie 1990).

Due to Finland's location within the mixing zone of polar and tropical air masses, atmospheric pressure and airflow conditions present a high level of variation (Solantie 1990). High wind speeds, however, are very rare (Tammelin 1991). The average inland wind speed is 3 to 4 m/s, and winds are lowest in the summer (Tammelin 1991).

1.5.3. Topography

The general shape of the land ranges from broad, flat coastal plains to undulating or rugged inland hills. Approximately 80% of the land area lies below 200 m, and only 1.5% are located higher than 400 m above sea level (Tikkanen 1994). Current landforms have largely been shaped by the last continental glaciers which used to cover the whole country and receded only 10,000 years ago (Tikkanen 1994, Seppälä 2005). The massive ice sheets left the land covered with moraines, drumlins, eskers (Tikkanen 1994, Seppälä 2005), and the tens of thousands of lakes which constitute the lake district; the most extensive physiographic region of Finland (Kuusisto 2005). During the 20th century, the extent and density of man-made topographic features, such as roads, cultivations, and housing, has increased dramatically, and human influence can at present be considered the main modifier of topographic features (Tikkanen 1994).

Finnish landscape presents a high amount of natural fire barriers such as lakes, rivers, and bogs (Parviainen 1996). From fire danger point of view, the absence of rugged

mountainous terrain combined with the presence of extensive road network is another major factor that contributes to the absence of extreme fire danger in Finland.

1.5.4. Fire regimes

Finland lies within the boreal coniferous zone (Ahti et al. 1968) in which forest fire is considered as the principal natural process responsible for the renewal of forests (Rowe and Scotter 1973, Goldammer and Furyaev 1996). Some North American ecosystems, such as *Pinus contorta* var. *latifolia* (lodgepole pine) forests, are characterized by infrequently occurring, high-intensity stand-replacing crown fires (Johnson 1992, Brown 1994), but in Eurasia and especially in Fennoscandia, stand-replacing fires have not been found to be such a prominent feature (Saari 1923, Granström 1996, Pennanen 2002, Wallenius 2004). *Pinus sylvestris* is known to tolerate frequent low-intensity surface fires: pine trees older than 20–40 years are somewhat fire resistant (Kolström and Kellomäki 1993), and pine seeds are able to preserve partial germination ability even if charred (Sannikov and Goldammer 1996). *Picea abies*, on the other hand, may suffer lethal injuries in a slightest fire (Wallenius 2004) because of its superficial root system and thin bark (Cajander 1916).

Due to the human disturbance in the region, fire historical research methods have been unable to determine the natural fire regime and the significance of different types of fires to this part of boreal zone (Wallenius 2002, Pitkänen et al. 2003). Observations on mean fire intervals in Fennoscandia since 3000 B. P. until the end of 20th century have ranged between 20 years (Niklasson and Dradenberg 2001) and more than 300 years (Wallenius 2002) depending on region and time period. People arrived in Finland soon after the last Ice Age, approximately 9000 years ago (Edgren 1984). Presumably the most powerful type of fire-use, slash and burn agriculture, was first introduced in southern Finland around 2400–2000 B. P. (Huurre 2003). This land use form was at its most popular in the 16th and 17th centuries, and it remained widely practiced in eastern Finland until 19th century (Sarmela 1987). Large wildland fires were a fairly common phenomenon in Finland and Sweden until the end of 19th century (Saari 1923, Niklasson and Granström 2000). Silvicultural slash burning was to varying extent practiced from 1910 through 1960, but it was then replaced by the less expensive and risky mechanical site preparation techniques (Viro 1974, Anon. 1980, Parviainen 1996). As the slash-and-burn cultivation method got banned (Heikinheimo 1987), and active fire suppression policy took place, the yearly area burned started to decrease (Zackrisson 1977, Parviainen 1996, Niklasson and Granström 2000). The 20th century was characterized by diminishing fire size and yearly area burned (Parviainen 1996). By the end of the 20th century, the elimination of fires reached a point where fire-based ecosystem functions were considered endangered (Rassi et al. 2003).

1.5.5 Topical issues around forest fires

Biodiversity concerns have created more demand for the use of controlled fire, e.g. in the form of silvicultural slash burning or the burning of uncut stands, mainly applied in protected forest areas (Rassi et al. 2003). Fire use, however, has not risen to meet the ecological recommendation which for yearly area burned in Finland and Sweden is 5% of the cut area on dry and mesic sites (Granström 2001, Kuuluvainen et al. 2002). Reasons for this are linked to the disappearance of traditional fire use know-how, and the high operational costs combined with the fears of fire escaping or the other unwanted outcome of not being able to achieve the burning target (Anon. 1980). On the other hand, fire rescue

service, trying to carry out its primary duty, overuses resources in fire surveillance and fire suppression due to not being able to make realistic assessments of fire danger in different situations.

1.6 Aims of the study

The prevailing issues with controlled fire use and fire suppression operations stem from the lack of experimental knowledge and tested tools for assessing fire behavior. This study aims to provide experimental data on local fuel structures and the interaction of weather, fuel moisture, and fire behavior to facilitate the adaptation of existing fire danger prediction systems for Finland. The results of this study will improve the ability of forest managers and fire rescue service to assess the quality of burning conditions and to plan appropriate courses of action based on prevailing weather circumstances. The knowledge of vegetation type -specific fire danger characteristics will also benefit the application of controlled fire in a manner that will produce desired burning results (Albini 1976, Alexander 1982). The specific aims of this study are:

- to describe the development of point fire ignition potential in relation to stand structure, moss moisture, and fire weather, as indicated by the Canadian Fire Weather Index System (I)
- to examine fuel moisture regimes in moss-dominated surface fuels and varying canopy cover conditions, and model the variation using Finnish Fire Risk Index (II)
- to determine the typical characteristics of fire behavior in different stand structures (III), and
- to examine, how seasonal vegetation development affects the ability of Finnish Fire Risk Index, Fire Weather index, and Initial Spread Index to predict fire danger via observed fire activity at different stages of fire season (IV).

2 MATERIAL AND METHODS

2.1 Establishment of sample plots for studies I-III

Studies I-III are based on field data collected in the districts of Lammi and Padasjoki (61°12' N, 25°07' E) in Finland, within southern boreal region (Ahti et al. 1968) during the fire seasons of 2001 and 2002. Forty experimental plots were established in this region in *Picea abies* or *Pinus sylvestris* dominated stands at four structurally distinctive developmental stages: (i) clear-cut areas (0–5 years since cutting), (ii) open immature stands (age: 15–20 years), (iii) closed semi-mature stands (age: 30 years for *Pinus* and 40 for *Picea*), and (iv) closed, mature stands (age: 45 for *Pinus*, 60 for *Picea*) (Appendix 1). Following the Finnish site type classification theory (Cajander 1926), the chosen *Pinus sylvestris* stands were classified as xeric or sub-xeric and *Picea abies* stands mesic or herb-rich heath.

In Finland, forestry land covers 86% of the land area (Finnish Forest Research Institute 2000), and most stands experience occasional management; if nothing else, a final cutting at the age of 60–120 years. As a result of commercial forestry practices getting more

extensively practiced during the latter half of 20th century, the forests have become structurally simpler and younger (Finnish Forest Research Institute 2000, Wallenius 2002). *Pinus sylvestris* or *Picea abies* dominated stands together cover nearly 90% of the forest area (Finnish Forest Research Institute 2000). Close to 80% of forests are under 100 years old, and since the 1950s, the median stand age in southern Finland has shifted from 40–60 years to 20–40 years (Finnish Forest Research Institute 2000).

The initial selection of stand types (i.e. fuel types) was designed to satisfy two general objectives: 1) to keep the study focused on stand structures that are most common in the Finnish forest landscape, and 2) to test the widest available range of structural stand properties assumed to contribute to fire danger. The preliminary fuel type classification based on dominant tree species, site type, and approximate age was supported by the fact that these variables are also being used for forest management mapping purposes and are familiar to forest managers.

The homogeneity of the experimental plots of a certain fuel type was the first priority in the plot selection. To achieve comparable plots, the stand basal area of the dominant tree species was set to be at least 85% of the total basal area; in reality, the minimum proportion of the dominant species ended up being > 90%. The effects of topographic variation on local weather and fire spread were considered unwanted for the purpose of this study and eliminated by including only sites with level terrain. To avoid disturbance from natural fire barriers, sites including moist depressions and ditches were disqualified.

A rectangle 30 × 30 m in size and surrounded by a 5-meter-wide buffer belt of similar vegetation was chosen for the general plot layout based on fire behavior field studies made in Canada (Alexander and Quintilio 1990), Sweden (Schimmel and Granström 1997), and Portugal (Viegas et al. 2002). Thirty-meter-long fireline is among the smallest used in experimental fire studies (Alexander and Quintilio 1990). This size was, however, considered the best option for this study due to limited availability of stands that would have had large enough areas of homogenous terrain to accommodate bigger plots. Symmetrical plot layout was applied to be able adjust the burning experiments to prevailing wind directions.

Standard forest inventory measurements were carried out and used as input for the KPL-program (Heinonen 1994) to calculate average stocking, dbh, and height of the dominant tree layer. Additionally, the number and height of tree seedlings were determined on each plot on nine systematically placed circles (radius 1.78 m). Estimates of the canopy openness and the effective leaf area index (Frazer et al. 1999) were produced with fisheye photography and Gap Light Analyzer Version 2.0 imaging software (Frazer et al. 1999). The composition of surface vegetation was defined using species cover percentage inventories on 6–9 systematically placed quadrates of 0.5 × 0.5 m. The heights of the shrub and herb vegetation and moss-humus layers were measured on 19 systematically placed 0.5 × 0.5 m quadrates on each plot. The loads of dwarf shrubs and herbaceous plants were calculated based on coverage inventories and cover-biomass information retrieved from an earlier study carried out in the study region (Muukkonen and Heiskanen 2005).

Downed woody fuels were inventoried on the nine seedling inventory circles adapting principles from North-American studies (Brown 1974, McRae et al. 1979). In our study, downed woody material was inventoried in four diameter classes: 0–1.0 cm, 1.1–3.0 cm, 3.1–7.0 cm, and > 7.0 cm. The total number of twigs and branches, and the length of every fifth branch were recorded for each diameter class. Diameter and height from the ground were measured on every stump. In downed tree crowns, we measured the length of stem, diameter at the distance of 1.3 from the root of the stem, number of branch whirls, and the

number, length, and average diameter of branches in every 1st, 5th, and 9th branch whirl. The loadings of dead woody fuel components were calculated as a product of material volumes per area (derived from dimension class frequencies) and a fixed mass density per volume value.

2.2 The development of ignition potential (I)

The objectives of this study were to define under which conditions a point ignition would develop into a self-sustained fire, test the ability of the Canadian Fire Weather Index System (hereafter: the FWI System) and the Finnish Fire Risk Index (hereafter: the FFI) to explain the development of ignition potential, and form fire weather index –based predictions of fire day frequencies for different stand types. Forest fire ignition potential was studied in conjunction with fuel moisture content.

Data for this module was collected on 61 days of which 38 included ignition testing and 23 days were evaluated to have no ignition potential because of rain. In the ignition tests (Fig. 2A), a burning match was brought into contact with the forest floor surface layer, and time was recorded when the fire had spread to a distance of 30 cm. A maximum time limit of five minutes (or minimum rate of spread > 0.06 m/min) was set to ease the determination of a successful ignition and manage the amount of time spent for an individual test. The minimum limit set for an acceptable rate of spread was likely lower than a sustainable flaming front would present. The ignition attempt was replicated with a maximum of five matches per test location to avoid failing to observe existing fire potential due to misplaced match, or initial flame being extinguished by wind before the flame properly reached the fuel. The ignition tests were performed in between trees, because moss layer next to a tree is often compacted and less covering due to roots, litter accumulation, and canopy competition. Destructive fuel moisture sampling (II) (Fig. 2B) was carried out within 1m² of the location of an ignition test.



Figure 2A) Point ignition tests were carried out within an area delineated using a low steel cylinder, Ø 50 cm. **2B)** Surface fuel moisture samples were cut using a 15cm x 15 cm steel frame. (Photos: Pauli Pihlajamäki)

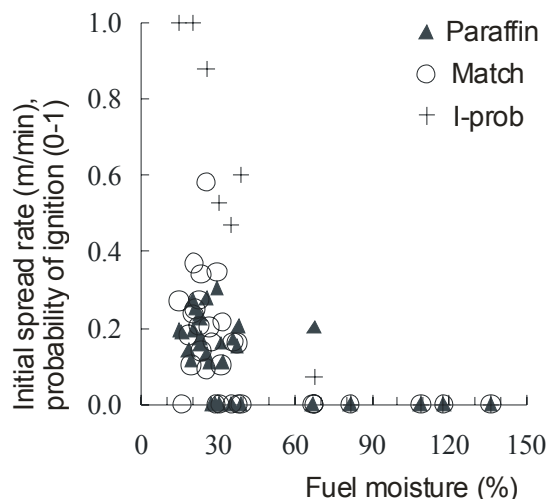


Figure 3. Ignition success in relation to the fuel moisture content and ignition source (match vs. n-paraffin). The initial spread rate was measured over a 30-cm distance, the average probability of ignition (I-prob) was determined as a proportion of the number of successful ignitions out of the number of ignition attempts at fuel moisture intervals of 5 percentage points. (I)

The match ignition method has previously been used in similar studies in Canada (Lawson et al. 1993) and Sweden (Granström and Schimmel 1998). The ability of this low initial heat impact (the energy release from a single match ranging around 20–30 Wm⁻² (Latham and Beer 1995)) method of reflecting surface fire potential in relation to fuel moisture was verified in a separate test series and found to produce fire potential results identical to those with a more powerful ignition device (Fig. 3).

Ignition success percentages were analyzed in relation to stand structural properties, pre-classified stand types, and noon LST values of the FWI System and the FFI. In addition, the number of average stand-type-specific fire days was estimated based on index-ignition regression fittings and weather data of years 1991–2002.

Runs of the FWI System were done using the improved standard version of 1984 (Van Wagner and Pickett 1985, Van Wagner 1987). No special adjustments were made on the standard effective day-length factors, since the impact of different latitudes on model output levels has been considered insignificant (Van Wagner 1987). The FWI System requires the input of daily noon weather readings of temperature, relative humidity, 10-m wind speed, and 24-h precipitation, and yields seven indices that predict various aspects of fire behavior. The standard output of the FWI System consists of the Fine Fuel Moisture Code (FFMC) calculated based on air temperature, relative humidity, wind speed, and rain; Duff Moisture Code (DMC) based on temperature, relative humidity, and rain; Drought Code (DC) based on temperature and rain; Initial Spread Index (ISI) based on FFMC and wind speed; Buildup Index (BUI) based on DMC and DC; and Fire Weather Index (FWI) based on ISI and FWI (Van Wagner 1987). In their original application environment, the primary function of the first three codes is to estimate the moisture content using weather information in surface litter (FFMC), in loosely compacted duff of moderate depth (DMC), and in deep organic matter (DC) (Stocks et al. 1989). The fuel moisture codes function as a

bookkeeping system that adds moisture after rain and subtracts moisture for each dry day (Van Wagner 1987). The FPMC can range from 0 to 99 (Van Wagner 1987). The DMC normally ranges within 0–300, and the DC within 0–800 (Van Wagner 1987). With all the moisture codes, higher values indicate dryer fuel (Van Wagner 1987). The latter three codes are derived using the moisture codes and considered to reflect rate of fire spread (ISI), amount of fuel available for burning, the availability defined by fuel moisture content (BUI), and frontal fire intensity and level of suppression difficulty (FWI) (Stocks et al. 1989). In relation to point ignition experiments, we chose to observe the FPMC as an indicator of fuel moisture in the very surface of the fuel where the ignitions took place, the ISI as an indicator of the initial spread rate, and the FWI as an indicator of general fire danger (Van Wagner 1987). The DMC, DC, and BUI codes were excluded, because they are structurally designed to measure and indicate the amount of fuel available to burning which was not of interest in our experiments.

Developed observing fuel moisture and fire behavior in a reference fuel type, i.e. a mature jack pine (*Pinus banksiana* Lamb.) or lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.) stand, in Canada (Van Wagner 1987), the FWI System might not describe those processes adequately in other fire environments. The system has, however, been found to function accurately for assessing fuel moisture and fire danger in Sweden (Granström and Schimmel 1998) and fuel moisture and burned area in southern Europe (Viegas et al. 1999, 2001). The FWI System is also being used as a national fire danger warning system in New Zealand with minor adaptations (Anon. 1993, Alexander 1994).

Ignition success was calculated as the percentage of successful ignitions out of the daily trials and averaged for different stand types. Significant differences in the daily ignition success percentages between all stand types were defined using paired sample *t*-tests (SPSS program, version 10). Relations between the ignition results and structural properties of the stands (stocking, basal area, stand dominant height, total volume, and crown height) were studied using correlation and regression analysis. Canopy openness (the percentage of open sky seen from beneath a forest canopy), effective leaf area index (Frazer et al. 1998), and total transmitted radiation below the canopy as a percentage of the total above-canopy radiation were produced by analyzing hemispherical photos with Gap Light Analyzer (Frazer et al. 1998) and used as independent variables in modeling the ignition potential.

The ignition percentage observations of each stand type were initially compared with the FFI and the FPMC, ISI, and FWI codes of the FWI System. The FFI, however, had no correlation with ignition success, and the further analysis was performed using only the FPMC, ISI, and FWI codes.

To model the interdependence of daily fire weather code readings (X) and ignition percentage values (P), we used equation form used in a study of Lawson et al. (1993):

$$P = \frac{1}{1 + e^{(\alpha_i - \beta_i X_i)}} 100, \quad (1)$$

where α_i and β_i are estimated parameters ($\alpha > 0$, $\beta > 0$), and i in this study is FPMC, ISI, or FWI. The curve fitting was carried out using nonlinear regression analysis function (SPSS, version 10). The calculations were done separately for early (June, July) and late season (August) test periods due to an observed discrepancy in the ignition results during

those stages of fire season. After finding the best-fit values for parameters α and β (Eq. 1), the equation was solved for index value $X_{i90\%}$ at the chosen high ignition percentage value, 90% ($= P_{max}$) as follows:

$$X_{i90\%} = \frac{\ln(100 / P_{max} - 1) - \alpha_i}{-\beta_i}. \quad (2)$$

In Equation 2, $\alpha_i > 0$, $\beta_i > 0$, and i : FFMC, ISI, FWI. The outputs of these calculations were used as minimum index values that would indicate the occurrence of a potential fire day in the dataset of regional weather for fire seasons 1991–2002. The potential fire day frequencies were calculated by combining the early and late season regression analysis results for each of the indices and averaging the fire day frequencies of the three codes.

2.3 Moisture content variation in moss-dominated surface fuels (II)

The aims of this study were to examine if there were significant differences in surface fuel moisture conditions between the studied fuel types and to test the ability of the FFI (Heikinheimo et al. 1998, Venäläinen and Heikinheimo 2003) to model the surface fuel moisture variation. The FFI was initially developed to estimate the volumetric moisture content of a 6-cm-deep organic layer (consisting of litter, moss, and humus) in clear-cut areas as a function of precipitation and evaporation. The evaporation function of the model uses the input of air temperature, relative humidity, 10-m wind speed, and surface net radiation (Heikinheimo et al. 1998, Venäläinen and Heikinheimo 2003). The index gets calculated every three hours (at 00:00, 03:00, 06:00, 09:00, 12:00, 15:00, 18:00, and 21:00 hours) during fire season. In the analysis, we used the daily noon LST values, provided by Finnish Meteorological Institute using interpolated weather information from the national weather station network (Venäläinen and Heikinheimo 2002).

The FFI is scaled to range between 1.0 and 6.0, 1.0 indicating the lowest and 6.0 the highest possible fire risk in terms of fuel moisture.

The surface dimensions of a fuel sample were 15 cm × 15 cm. The samples included surface litter, and green and brown parts of the growing moss down to the more compact humus layer (Fig. 2B). The sampling was performed in 6–7 stand types on 47 days during June, July, and August 2001. Gravimetric field fuel moisture content was calculated using formula:

$$(FW - DW) / DW \times 100\%, \quad (3)$$

where FW is the fresh weight of a sample and DW the measured dry weight of the same sample after 24 hours drying at 105°C. Oven-dry sample weights were also used to calculate dry matter surface fuel loads (kg m^{-2}) for each stand type. The fuel moisture sampling was carried out in the afternoon, because that is when fine fuel moisture and relative humidity are at their lowest and fire danger is considered to be at its highest (Van Wagner 1987).

In the analysis, we assumed that surface moss moisture content is mainly a product of boundary layer atmospheric conditions, i.e. weather conditions close to moss layer surface as modified by canopy. The impact of soil moisture on the wetting of surface moss layer was considered negligible, because mosses, lacking roots, are dependent on precipitation to gain water (Proctor 1981). Because forest mosses also lack stomatal control (Proctor 1981), their moisture loss dynamics are determined by boundary layer weather conditions, such as solar radiation, relative humidity, and wind speed, in the manner of dead fine fuels (Norum 1982, Schimmel and Granström 1997). The direct impact of canopy on boundary layer weather conditions could not be defined, because reliable equipment for measuring the amount of radiation or precipitation under different canopies for this amount of experimental stands was not available. Therefore, instead of analyzing at first the impact of canopy structure on boundary layer weather, we limited our analysis to the relationship between canopy structure and resulting surface fuel moisture.

Paired samples t-test of the SPSS program, version 10 (SPSS Inc., Chicago, Illinois) was considered the best alternative for the analysis taking into account the quality of the data (non-equal variances, correlation between observation series of different stand types) and the aim of the study to provide estimates of the direction and magnitude of moisture content differences between stand types. This analysis approach has been applied in a similar study, to track significant differences in duff moisture between sheltered and less-sheltered sites (Wotton et al. 2005). Correlation analysis was used to test for dependency between the plot-wise moisture content (as sub-sets of June, July, August, and total season) and corresponding stand characteristics: canopy openness, leaf area index, and canopy depth.

Regression models of the negative exponential type were developed between the daily noon FFI values and the corresponding stand type -specific afternoon moisture content values (MC_{stand}) as:

$$MC_{stand} = a_i \times \exp(b_i \text{FFI}), \quad (4)$$

where a_i and b_i are stand type -specific parameters ($a_i >$ the observed maximum moisture content in stand type i , $b_i < 0$) estimated using nonlinear regression analysis tool (SPSS, version 10, SPSS Inc., Chicago, Illinois).

2.4 Fire behavior (III)

The aims of this study were to observe the rates of spread (ROS), flame height, and fireline intensity in the selected stand types, and relate the observed fire behavior patterns to fire weather and stand structure.

Burning experiments were carried out on the total of 34 experimental plots during 14 days in the driest available conditions during fire season 2002. Two to four plots were burned on each burning day. The criterion in daily plot selection was two-fold. Firstly, each plot was to represent a different fuel type to be able to observe differences in the development of fire danger between stand types. Secondly, the distance between the daily target plots had to be as short as possible to minimize crew transition times. Regional FFI values and *in situ* precipitation surveillance were used to evaluate when the conditions were suitable for burning. For fire weather, the requirement was the FFI value of above 3.0; this threshold was chosen based on the findings of study II on the development of fuel moisture

in relation to the variation of the FFI. The FWI System was not available for predictive purposes during this field experiment series. No upper limit was set to the acceptable extremity of fire weather conditions.

The use of on-site weather stations is recommended for experimental fire behavior studies, especially to ensure accurate wind readings. In this case, an on-site weather station was not an option due to a large number of plots spread out within a wide area, a tight burning schedule, and resource limitations. Further on, it would have been difficult to apply a weather station adequately on the majority of the experimental plots, located in the midst of a densely forested landscape presenting a lot of topographic micro-variation. Instead, meteorological data for the fire weather index calculations were retrieved from the national weather station network of the Finnish Meteorological Institute which measures precipitation at about 200 locations, air temperature, air humidity, and wind speed at 160 locations, and solar radiation at 55 locations (Venäläinen and Heikinheimo 2002). The network had a good coverage over our study area, the nearest station being located only 5–20 km from our study plots and the three next closest weather stations surrounding the area within a radius of 40–60 km. The interpolation of weather data was done using the spatial statistics method of kriging (Ripley 1981) with a program especially designed for climatologic applications in forestry (Henttonen 1991). The method has been proven to provide reasonably good local estimates of all weather variables (e.g. Vajda and Venäläinen 2003) needed for this study. From fuel moisture status point of view, the accuracy of precipitation was assessed slightly problematic, because local rain showers can create very high spatial variation (Venäläinen et al. 2005). To keep track of localized rain events, eight rain collectors were located on the study area and collected daily.

Prior to each burn, air relative humidity and temperature were recorded using a portable probe (model HMP41, Vaisala) and destructive fuel moisture sampling was carried out. In-stand wind measurements during the experiments were carried out using hand-held anemometer. The momentary wind speed and direction (with 45° rounding) were measured at 2-m height at two-minute intervals during active burning. The measurements were carried out far enough from the fire front to avoid the influence of convection caused by the burns. Attention was also paid to not holding the device in a wind-shadow created by individual trees or bushes. The accuracy of the anemometer was later tested in a wind tunnel of the Finnish Meteorological Institute. Some systematical dysfunctions were found, and the measured wind speeds were converted to actual wind speeds by applying a corrective equation. To analyze the impact of in-stand wind speed on fire behavior, we calculated momentary and average wind vectors to the direction of the spreading fire.

Fire spread rate and flame properties without downwind or upslope effects are considered fuel-type specific standard characteristics and the cornerstones of fire behavior modeling (Rothermel 1972). The slope effect was eliminated in our experiments during the initial plot selection. To make fire behavior observations without downwind effect, small 5 m × 5 m upwind experiments were carried out on the buffer belt of each plot prior to the larger experiment. After the upwind burning experiment, the windward edge of the 30 m × 30 m size plot was ignited with two drip torches, and the fire was allowed to burn freely with the wind to the opposite edge. The spread rate of the fastest part of fire front and flame heights were observed visually on two sides of a burning plot at the spread distance of 7.5, 15.0, 22.5, and 30.0 m from the ignition line. The control of the experimental fires was mostly done by selectively wetting surface fuels on downwind side of the plot boundary just before the experiment. After the fire front arrived at the opposite side of the plot or one

hour since ignition passed, it was extinguished using a hose-nozzle system mounted around the plot.

Instead of flame length, flame height was observed because of its more accurate measurability in field conditions with limited resources available for observation (Simard et al. 1989). Torching was recorded to have happened when a tree was torched at or over the height of three meters. That threshold was chosen because it was fairly close to the highest dead branch lower limits found among the experimental plots and easy to estimate being twice the height of the 1.5 m marker poles.

The depth of burn in moss and humus layer was observed using 19 t-bar depth-of-burn pins (McRae et al. 1979), placed systematically to cover the whole plot and controlled before and after a burning experiment. An approximate burning coverage was determined to describe the development of flammability in different stand types while fire weather conditions evolved from low to moderate and high fire danger. Burn coverage was calculated as the proportion of the 30-meter-long spread distance achieved within a maximum time-lag of one hour and averaged for each stand type. Since most of the tested stands had only three replicates, new sub-data groups were formed by pooling structurally similar stand types: *Picea_60* and *Picea_40*, *Pinus_45* and *Pinus_30*, *Picea_15* and *Pinus_15*. The impact of increased fire weather hazard on burning coverage in those stand types was modeled running regression analysis for each sub-group using the FFI and FWI code values as independent variables.

Regression analyses were run for the plot average spread rates using the respective average positive or negative mid-flame wind speed as independent variable. The influence of surface fuel moisture content variation on wind-ROS relationship was also examined by differentiating the burning experiment dataset based on recorded surface fuel moisture contents. Relationships between spread rates and FFMC, ISI, FWI, and FFI values were studied using Pearson's correlation analysis. In addition, correlations between flame height and FFMC, BUI, FWI, and FFI were examined.

Byram's fireline intensity (kW m^{-1}) was calculated using formula (Byram 1959, Alexander 1982):

$$I = H \times W \times R, \quad (5)$$

where H is the low heat of combustion (kJ kg^{-1}), W is the weight of fuel consumed (kg m^{-2}) in the flaming zone, and R is the rate of spread (m s^{-1}). The value of H was set to 18700 kJ kg^{-1} commonly used in fire behavior studies (Albini 1976, Schimmel and Granström 1997). The average moss layer density, $0.129 \text{ kg m}^{-2} \text{ cm}^{-1}$, was derived from the fuel moisture samples (II) and used to calculate the fuel consumption from the burned fuel volume measured as a product of the coverage and depth of burn. A single moss layer density value was considered adequate due to general shallowness of organic layers; the maximum moss depth was only 12 cm (II, III). Defining the exact nature of depth-related variation of moss density on each site would have been very time-consuming since there were no previous studies on the subject. Since shrub layer fuel loads were considered minor, they were not directly measured. Fuel consumption in this layer was estimated by multiplying the initial cover-based estimate of shrub load by the observed burn cover (%). Fuel consumption in another minor component, fine downed dead woody fuels, was roughly estimated in a similar manner by multiplying initial fine (diameter $< 1.0 \text{ cm}$) woody fuel load by moss layer burn cover (%).

A universal methodological problem with the fuel consumption –based approach is its inability to capture the actual fireline intensity (Smith et al. 1993). In most fuel materials, a part of the mass loss usually takes place after the flaming front has passed. However, in field burning experiments, it is impossible to define which part of the fuel consumption occurred while the main flaming front was present and which part came after the front had moved forward. Since this method observes the total fuel consumption, it tends to overestimate the actual frontal fireline intensity. In this study, plots were extinguished using drizzling water right after the plot had burned through which minimizes the glowing consumption to some extent. It is clear though that some error in the fireline intensity values still remains due to not being able to isolate the physical reaction of interest during the test. The intensity values should therefore be considered rough estimates that primarily indicate relative differences in fireline intensity levels between different stand types and weather conditions.

2.5 Seasonality of fires (IV)

In this study, the aim was to observe seasonal trends in the number of fires and area burned in Finland, and to test the ability of the FFI (Heikinheimo et al. 1998, Venäläinen and Heikinheimo 2003) and the FWI and ISI codes of the Canadian Fire Weather Index System (Van Wagner 1987, Stocks et al. 1989) to explain fire activity during different stages of seasonal vegetation development.

Fire event data consisted of unpublished national Finnish fire records 1996–2003 which had been collected by local fire officials and filed to the central database of the Rescue Service. Information on each fire event consisted of date, time, location, area burned. The reports did not include information on fire weather, fire behavior, fuel type, or the type of suppression needed to put out the fire. The dataset contained a total of 7675 forest fires. The yearly average of fire occurrence was 959 fires per year and total area burned 357 ha. The range of final fire size was 0 to 200 ha, and the average fire size 0.37 ha.

Preliminary analysis on daily number of fires and daily area burned in relation to date, and effective temperature sum was carried out for all forest fire records in the national database. The analysis on fire activity in relation to fire weather indices and effective temperature sum was carried out for three study areas Kauhava (63°07' N, 23°02' E), Jyväskylä (62°24' N, 25°40' E), and Tampere (61°25' N, 23°37' E). For Kauhava region, data on fire weather and temperature sum were available for years 1996–2003, for Jyväskylä region for years 1996–2001, and for Tampere region for years 2002–2003. Fire events for each location were accepted if they occurred within a 140 km × 140 km rectangle surrounding the exact location of the station. The extent of an individual study area was chosen as a compromise to include as many reported fires as possible, but to keep effective temperature sum and the fire weather index values still representative of the study area. With the 140 km × 140 km rectangle the potential maximum distance of a fire and the weather station was 99 km. This selection criterion produced a dataset of 639 fires that burned a total of 282 ha, the average daily area burned being 0.44 ha.

The FFI and the ISI and FWI codes of the FWI System were used as indicators of fire weather conditions. The FFI is the only system used operationally for fire danger assessment in Finland. The FFI estimates fuel moisture development in a fairly thick layer of organic surface fuel and could be characterized as an indicator of fuel available for burning similar to the BUI in the FWI System (Van Wagner 1987, Stocks et al. 1989). The

ISI, an indicator of the initial fire spread rate, would theoretically be the best match for the daily area burned. The FWI code is considered a good indicator of general fire danger (Van Wagner 1987, Stocks et al. 1989), and was found to be a good predictor of ignition potential in this fire environment (I). The FFI and the FWI System's improved standard version of 1984 (Van Wagner and Pickett 1985, Van Wagner 1987) calculations for the three study regions were made retrospectively using weather data provided by a nationwide network of permanent weather stations maintained by the Finnish Meteorological Institute (Venäläinen and Heikinheimo 2002).

Effective temperature sum (unit: degree days or d.d.) is a method used in the modeling of phenological development of plants after winter dormancy and defined as the sum of those daily mean air temperatures that exceed the minimum threshold temperature considered effective (e.g. Sarvas 1972, Lappalainen 1994, Heikinheimo and Lappalainen 1997). In Finland, +5 °C has been the most used temperature threshold value (Sarvas 1972, Heikinheimo and Lappalainen 1997). The daily values of the effective temperature sum (Tsum) for this study were calculated using equation:

$$Tsum = \sum_{d=1}^n (T_d - T_{min}) \quad \text{if } T_d \geq T_{min} \text{ } ^\circ\text{C} \quad (6)$$

where T_d is the daily mean temperature, and the required minimum temperature, T_{min} , is 5°C. Applying studies of the seasonal growth dynamics of common understory species *Vaccinium myrtillus* and *Vaccinium vitis-idaea* (e.g. Havas and Kubin 1983), we chose four divisions of the effective temperature sum to determine stages of fire season when the fire danger prediction ability of fire weather indexes might be altered due to vegetation development. These stages were A) the period between snowmelt and the start of the new growth when surface fuel layer mainly consists of dead fuel material (Tsum 0-50), B) the period of rapid live fuel accumulation (Tsum 50-250), 4) the period of maximum live fuel load (Tsum 250-900), and D) the period of growth slow-down and curing (Tsum >900).

The fire potential or fire danger that fire danger prediction systems assess are not directly measurable variables but abstractions that may be described e.g. by observations of fire activity (Andrews et al. 2003). Number of fires and area burned are the most often used dependent variables in analyzing the performance of fire danger rating systems (e.g. Krusel et al. 1993, Andrews et al. 2003). In this study, we used fire-day, multiple-fire-day, and large-fire-day to indicate fire activity. The occurrence of a single fire on a certain day may not provide accurate reflections of fire danger in a fire environment such as Finland where nearly 90% of ignitions are human-caused, and reported fires may not have presented much spread potential. As a demonstration of this, 11% of the fire events in our fire database had a reported final area burned of less than 1 m². The occurrence of several fires on the same day is a more plausible indicator of high fire potential and ignition though the significance is still to some extent inflated by the accuracy of reporting and human factors involved with fire initiation.

Among the common fire activity indicators, large daily area burned and large fires are most dependent on the occurrence of favorable fire weather conditions. Using these variables in the statistical performance evaluation of fire weather index systems is, however, problematic due to the generally low number of actual large fires. Large fires are defined as fires that are difficult or impossible to control and that, within the area and time

period of interest, account for very small proportion (2–5%) of fire events but are responsible for the majority (up to 95–98%) of total seasonal area burned (Weber and Stocks 1998). The application of actual large fire analysis is especially complicated in Finland where yearly area burned has diminished drastically during the past century and earlier large fires have become extinct (Parviainen 1996, Niklasson and Granström 2000). To ensure sufficient amount of observations for the analysis, we decided to reduce the acceptable size of a large fire so that the sub-dataset consisted of the biggest 20% of the observed fire events and 90% of the total area burned.

Logistic regression analysis using SPSS Version 12 binary logistic and multinomial logistic functions was applied to examine the relationship between fire weather indices and fire activity. Following the methodology used by Martell et al. (1987) and Andrews et al. (2003), the fire occurrence data were transformed into binary variables by determining the occurrence or absence of a fire-day (value for a day = 1, if one fire occurred; otherwise 0), a multiple-fire-day (value for a day = 1, if more than one fire occurred; otherwise 0), and a large-fire-day (value for a day = 1, if area burned is $\geq A$ (large fire); otherwise 0). In this data, the minimum area burned for a large-fire-day, as determined by the 90th percentile of total area burned, was 0.5 ha.

Probabilities of fire-day, multiple-fire-day, and large-fire-day were calculated using equation:

$$p(\text{fireactivity}) = \frac{1}{1 + e^{(-a-bx)}} \quad (7),$$

in which FFI, FWI, and ISI were covariate x , and a and b were output parameters of the model fitting. At first, logistic regression modeling was carried out for the non-stratified seasonal data to identify the general relationship between the fire activity variables and the FFI, FWI, and ISI. Then, logistic regression models were formed for four different stages of the growing season using the effective temperature sum values of 50, 250, and 900 d.d. as stage separators.

To evaluate the performance of the regression models, we calculated Hosmer-Lemeshow goodness-of-fit statistic (chi-square), pseudo- R^2 , and odds ratios. Hosmer-Lemeshow statistic is calculated by comparing the observed probability with the expected probability within each decile of risk (Hosmer and Lemeshow 2000). Pseudo- R^2 resembles the standard coefficient of determination but due to the mechanics of logistic regression usually returns very small values (Hosmer and Lemeshow 2000). Odds ratio indicates the increase or decrease in odds that an event will be in one outcome category when the value of predictor increases by one unit (Tabachnick and Fidell 2001).

3 RESULTS AND DISCUSSION

3.1 Ignition potential (I) and surface fuel moisture (II) in different stand structures

Main findings:

- Ignition potential was highest in *Pinus sylvestris* clear-cuts and lowest in closed *Picea abies* stands (I)
- Ignition resulted in self-sustained surface fires in 19–32% of trials in *Pinus* stands and in 5–12% of trials in *Picea* stands (I)
- Surface fuel moisture was lowest in *Pinus sylvestris* clear-cuts and highest in closed *Picea abies* stands (II)
- Closed *Picea* stands were significantly less flammable than closed *Pinus* stands (I, II)
- Surface fuel moisture content ranged 10–500% under closed canopy and 10–300% on open sites (II)
- Canopy cover correlated with ignition potential (I) and surface fuel moisture (II)

In *Pinus sylvestris* dominated stands, ignition tests resulted in self-sustained surface fires in 32.0 %, 24.0 %, and 19.3 % of cases in 0-, 15-, 30–45-year age classes, respectively (I). In *Picea abies* dominated sites, point fires sustained themselves in 12.0 % and 4.6 % of trials in the 0- and 40–60-year age classes, respectively (I). Clear-cuts therefore presented sustained surface fire potential two-to-three times more often than closed stands (I). The effect of dominant tree species turned out to be quite significant because *Pinus sylvestris* dominated stands were able to catch fire on roughly three times more frequently than *Picea abies* stands (I).

The ignition patterns were backed up by surface fuel moisture observations: moss moisture content was below 50% in open *Pinus* stands on nearly 40% and in closed *Pinus* stands on 8% of the sampling days but never dropped below 50% in closed mature *Picea* stands (II). Considering that fuel moisture of 30% was defined as the maximum moisture content that would enable a spreading fire (Fig. 3) (I), closed *Picea* stands remained quite far from flammable during our sampling period. Variation in surface fuel moisture was widest, 10–500%, under closed canopy (II). The day-to-day changes in moss moisture content were quite sharp (II) highlighting the responsiveness of this fuel material to atmospheric conditions.

Canopy depth and effective leaf area index (an output variable of the Gap Light Analyzer, Frazer et al. 1999) correlated significantly with the ignition success percentage, the correlation coefficient ρ being -0.575 ($p < 0.005$) and -0.582 ($p < 0.005$), respectively (I). For surface fuel moisture significant correlations were formed with effective leaf area index (Fig. 4) and canopy openness (ρ : 0.68 and -0.84 , $p < 0.001$) (II). Finding correlations between canopy variables and surface fuel moisture seems logical since leaf area indices and other canopy gap descriptors can be used to assess boundary layer weather conditions, such as below-canopy radiation (Canham et al. 1990, Pukkala et al. 1991). Canopy cover is known to decrease the amount of solar radiation (Baldocchi and Vogel 1996), support higher and steadier relative humidity levels, and reduce wind on the forest floor (Oke 1987, Kunkel 2001). The presence of closed canopy is likely to decrease ignition and fire spread potential through maintaining higher surface fuel moisture levels (Kunkel 2001).

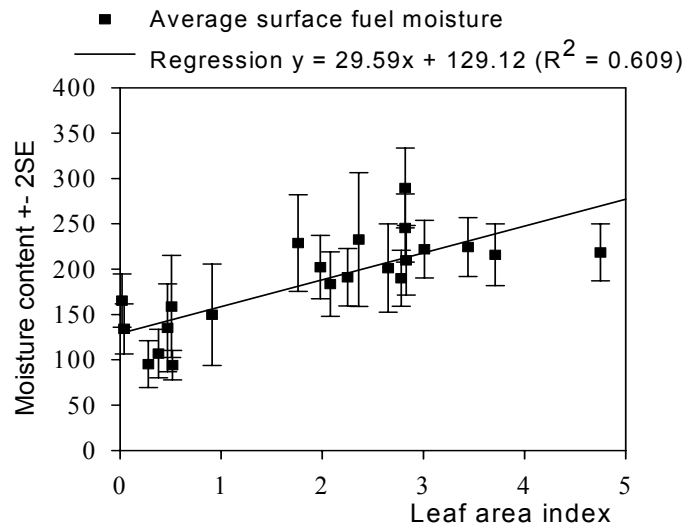


Figure 4. The average moisture content (\pm 2S.E.) of surface fuels in relation to leaf area index. Estimated linear regression and coefficient of determination indicated. (II)

3.2 Fire behavior in relation to stand type, wind, and fuel moisture (III)

Main findings:

- Tested stand types were mainly able to support surface fires
- Closed *Picea abies* stands did not produce self-sustained fires
- Fire spread was slow on clear-cuts despite of higher in-stand wind speeds and dry fuel material
- Open, immature and closed *Pinus sylvestris* stands presented the fastest spreading and most intensive fires (Appendix 1)
- In open, immature and closed *Pinus sylvestris* stands, in-stand wind speed explained well fire spread rate
- Torching was related to dead-branch height and most common in open, immature or closed, semi-mature *Pinus* stands (Appendix 1)

The outcome of the line ignition experiments ranged from self-extinguished or weakly smoldering fires to fast surface fires presenting occasionally powerful torching (III). The test series repeated the ignition potential (I) and fuel moisture (II) findings in one respect: within the experienced low-to-moderate fire weather conditions, there were no complete plot burns in the closed *Picea abies* stands, most ignitions dying at the starting line. With the clear-cuts and closed *Pinus* stands, the order, however, was now different from fuel moisture and point ignition potential findings: the 15–45-year-old *Pinus* stands carried fire more efficiently than clear-cuts which in most cases sustained very slowly spreading fires. In the 15–45-year-old *Pinus* stands, fire spread rates ranged 0.1–3.4 m min⁻¹ and average flame heights 0.3–3.5 m (Appendix 1). In *Pinus* clear-cuts, spread rates were 0.3–0.5 m min⁻¹ and average flame heights 0.3–0.6 m (Appendix 1). Poor fire spread in clear-cuts was slightly unexpected considering that surface fuel material there was very dry and mid-flame

wind speeds highest among the tested stand types. Low burning potential during the early phase of stand development is in accordance with the findings of Schimmel (1993) and Schimmel and Granström (1997) despite the different mechanics behind the fuel status. In those studies, the post-burn development of site flammability was associated with successional changes in moss species composition, the less flammable species dominating recently burned, open sites and being gradually, along the proceeding canopy closure, replaced by structurally more flammable forest mosses (Schimmel 1993, Schimmel and Granström 1997). In our study, no significant differences in species composition were detected and lower fire spread rates in clear-cuts were likely a result of decreased moss porosity and disrupted fuel layer continuum due to cutting and soil preparation activities and slash accumulation. The clear-cuts also had higher amounts of live understory vegetation than the other fuel types.

Fire spread rates in closed and semi-closed *Pinus sylvestris* stands were comparable to those observed in *Pinus banksiana* Lamb. (i.e. jack pine) stands (Stocks 1987, 1989) or in mature *Pinus contorta* Dougl. var. *latifolia* Engelm. (i.e. lodgepole pine) stands (Lawson 1973). No published studies of fire behavior were found for shaded and humid micro-climate conditions similar to our closed *Picea abies* stands (Appendix 1). The lack of such studies likely stems from the difficulty of achieving the optimal combination of severe fire weather and adequate safety measures to burn this type of stands because they, when eventually sufficiently dry to burn, are structurally highly susceptible to develop a crown fire. Our observations suggest that under non-extreme fire weather conditions closed *Picea abies* stands would function as fire breaks, whereas closed *Pinus sylvestris* stands would be responsible for fire spread across forest landscape. This perception has earlier been expressed by many practical observers of forest fires (e.g. Osara 1949). The natural habitat partitioning theory behind the Finnish forest site type classification (Cajander 1916, 1926) and numerous fire history studies have also indicated, that *Picea abies* stands would typically burn rarely but intensively or act as fire refugia (Zackrisson 1977, Engelmark 1987, Wallenius 2002) whereas *Pinus sylvestris* stands would experience frequent, usually low-intensity surface fires (Zackrisson 1977, Engelmark 1987, Sannikov and Goldammer 1996).

Mid-flame wind speed had the strongest influence on fire front spread rates in open, immature and closed *Pinus* stands (Fig. 5), as could be expected based on established knowledge on fire propagation (e.g. Anderson and Rothermel 1965, Rothermel 1972, Albini 1976, Viegas 1998a,b). The form of wind impact has been defined to be linear within low downwind speeds (Catchpole et al. 1998) and exponential or other curvilinear for wider range of downwind variation (Anderson and Rothermel 1965, Anderson et al. 1966). Despite of our experiments presenting a fairly narrow range of low wind speeds, exponential regression model gave the best fit between in-stand wind velocity and fire spread rate (Fig. 5). The low number of cases under the highest wind speed conditions (especially under the driest fuel conditions) caused some uncertainty in the modeling of wind-fire spread relationship. The average no-wind or upwind rate of spread in *Pinus* stand types was 0.5 m min^{-1} (Fig. 5).

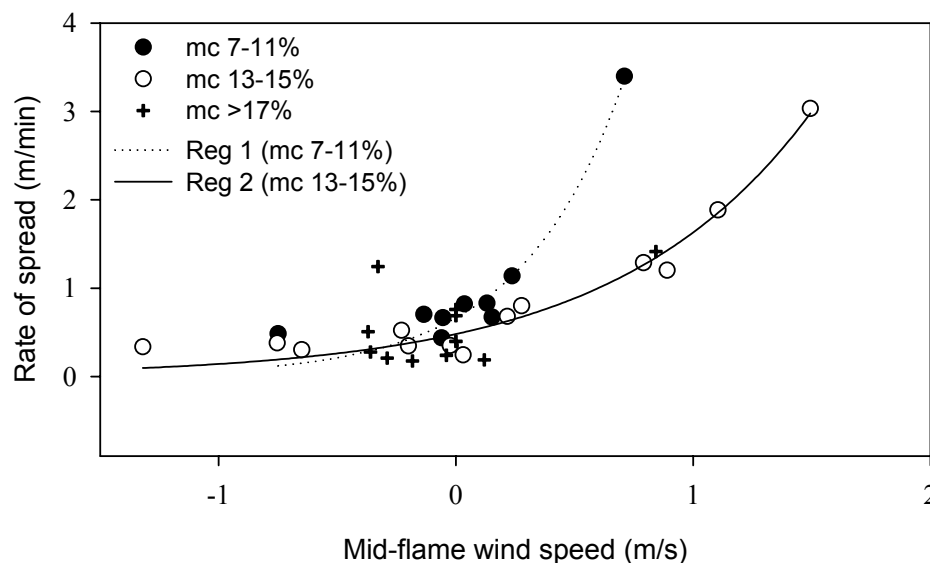


Figure 5. Fire spread rates observed in 15-45-year-old *Pinus sylvestris* stands under different surface fuel moisture and within-stand wind speed conditions (negative wind speeds refer to experiments where fireline was spreading against the wind). Equations for the exponential growth curves are 1) $y = 0.663e^{2.286x}$, ($R^2 = 0.96$, $p < 0.0001$) and 2) $y = 0.481e^{1.221x}$, ($R^2 = 0.96$, $p < 0.0001$). (III)

According to many laboratory studies, increase in moisture content should have decreased the rate of spread in a nearly linear manner (Anderson and Rothermel 1965, Catchpole et al. 1998). In our experiments, the effect of moisture remained somewhat vague: spread rates were clearly highest when surface fuel moisture was lowest (7-11%) but there was no consistent decrease in spread rate when moisture content increased from 13 to 40% (Fig. 5). Not observing clear fuel moisture effect likely resulted from lack of control over spatial micro-variation in surface fuel moisture. In conditions that based on the average of fuel moisture samples were considered moist, fire actually took the path of least resistance and spread through the driest patches of the plot. Having little choice in available fuel moisture levels, the observation ranges of fuel moisture were uneven and clustered in relation to wind speed variation (Fig. 5) further complicating this analysis.

The incidence of torching was inversely related to dead branch height. Torching of small trees having a low crown or taller trees with low-hanging dead branches was common even when the general fireline intensity was low. In this dataset, the expected correlation between torching and fireline intensity (Van Wagner 1973) did not get statistically significant, presumably because of the heterogeneity in tree size and dead branch conditions and the low variation of fireline intensity. The experiments showed that seemingly low-intensity fires may cause very different burning outcomes depending on the structure of stands being burned. If the objective is to produce a significant amount of burned, preferably dying trees for biodiversity purpose, prescribed burning of managed 45-year-old and older *Pinus* stands will unlikely be effective. On the other hand, if a surface fire with a

minor damage to dominant tree layer is desired, burning of younger or unmanaged stands (Appendix 1) will be unwise even under low fire danger conditions.

Calculated fireline intensities did not correlate with any of the fire weather indices, probably due to the general problems associated with the fuel consumption -based fire intensity estimates (Smith et al. 1993) and the narrow range of fire weather conditions available for this study. Fireline intensities calculated using the BEHAVE system (Burgan and Rothermel 1984) for 60-year-old *Pinus sylvestris* stands in Sweden were in the same range of 150–1300 kW m⁻¹ under moderate to extreme fire weather conditions (Schimmel and Granström 1997).

The important consideration of ecologically desirable fire type and fire intensity has been to some extent neglected in fire management in Finland. Prescribed fires have either been used to reduce slash and create beneficial soil nutrient dynamics after a clear-cutting (Viro 1974) or, more recently, to mimic the impacts of stand-replacing fires. Many *Pinus* sp. dominated ecosystems have been designated for frequent low-intensity surface burnings based on historic fire use patterns or ecological indicators (Arno et al. 1995, Neumann and Dickmann 2001). In Finland, however, prescribed underburning in *Pinus sylvestris* stands has been nearly non-existent even though it would be an ecologically sound (Sannikov and Goldammer 1996) and operationally less complicated option than high-intensity stand-replacing fires. The experiences of this study indicate that closed *Picea abies* stands become flammable very rarely, under such extreme fire weather conditions that the associated risk level most likely would not allow prescribed burning. According to several fire history studies, fire intervals for *Picea* dominated stands in Fennoscandia without human influence are so long that the currently experienced lag in the occurrence of intensive, stand-replacing fires in Finland would still be within the range of natural variation for this fire environment and would not necessitate artificial replacement (Granström 1996, Pennanen 2002, Wallenius 2004).

3.3 Seasonality of fires (I, II, IV)

Main findings

- Point ignition potential in the field experiments practically disappeared in August (I)
- Surface fuel layer had higher moisture content under closed canopy during the late season (II)
- In the national fire records, the number of daily ignitions presented three seasonal peaks but daily area burned only one substantial peak early in the season (IV)
- In the logistic regression analyses, the probability of ignition was clearly highest during the final part of the season, but the probability of large fires remained somewhat even throughout the season (IV)

In the field experiments, ignition potential disappeared almost completely and below-canopy surface fuel moisture remained at higher levels after July than earlier in the season without any significant change in fire weather conditions (I, II). The analysis of the national forest fire records 1996-2003 seemed to verify the weakening of flammability after early season (IV). The daily number of fires presented three seasonal peaks (Fig. 6A), but the average daily area burned showed only one pronounced, relatively brief, period of high

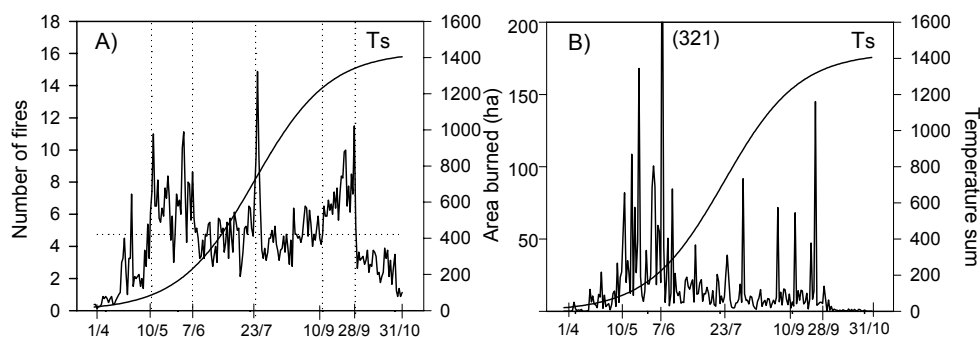


Fig. 6A) Average daily number of reported forest fire events (left axis) and the average accumulation of effective temperature sum (right axis) in Finland (340 000 km²) during fire seasons 1996-2003. **B)** Average daily burned area (left axis) and the average effective temperature sum (right axis) in Finland during fire seasons 1996-2003. (IV)

values occurring from May 8 through June 15 (Fig. 6B) (IV). During late season, area burned presented a longer period of slightly above average values (IV). In the logistic regression analysis of the regional fire records (IV), the strong human influence in the ignition frequencies and the difficulty of defining an informative but functional size for a large fire mixed the seasonal flammability results to some extent. The latest part of the season came up as the most active one (Tsum > 900 d.d.) in terms of the number of fires and somewhat equally active with the other stages in terms of area burned (IV). The logistic regression analysis did not detect the strongest peak in area burned during early season, present in the national data (Fig. 6B) (IV). This was likely caused by having to set the threshold for large-fire-day at a fairly low value to enable statistical analysis in the first place. Since the method was based on counting the number of days qualifying for a category, it made the late season's longer period of relatively small fires a more significant one than the early season's brief occurrence of the largest fires (IV).

The higher flammability of the early season, as indicated by our field test series and observed in the national fire records, is in accordance with model-based predictions (Larjavaara et al. 2004) and with the knowledge of seasonal vegetation development in this environment. Seasonal growth of herbaceous surface vegetation is a likely reason for the decline of area burned after mid-June because late-June is the point by which dwarf shrubs on average achieve most of the new season's shoot growth (Havas and Kubin 1983). The changing role of herbaceous vegetation component from a fire retardant (live) to a burning fuel (dead) has been incorporated in North American dynamic fire behavior fuel models (Scott and Burgan 2005). A normal fire season in Fennoscandia does not present a comparable mid-season shift from live fuel into dead fuel, but live herbaceous plants tend to stay alive and retain relatively high moisture content levels until the end of the season. The seasonal changes of leaf moisture content in ericaceous dwarf shrubs are relatively minor: in some *Vaccinium* sp., the foliar moisture has been found to decrease from 134% in the early summer to 105% in the end of the summer (Loomis and Blank 1981). By the time the seasonal foliar moisture changes occur, the general weather seldom creates extreme fire danger because of increased rain, higher relative humidity, and lower air temperatures (Drebs et al. 2002), and the seasonal change in sun's position between will have diminished the amount of solar radiation on forest floor (Bonan 2002) and subsequently

evapotranspiration from surface fuel layer (Byram and Jemison 1943). Therefore, if the seasonal dynamics of herbaceous plants were to be included in a Finnish fire danger prediction system, the role of this function would mainly be to estimate when this fuel component achieves its maximum load and decrease the fire potential accordingly in those fuel types where a significant herbaceous component is present (Appendix 1).

3.4 Applicability of fire weather indices (I, II, III, IV)

Main findings:

- The FWI code of the FWI System correlated strongly with ignition potential during the early and mid-parts of fire season (I)
- The FFI formed significant regressions with the development of surface fuel moisture in most stand structures (II)
- Neither the FWI System codes nor the FFI correlated with the observed fire behavior (III)
- The FFI, FWI, and ISI explained fire activity most reliably during mid-season (IV)
- During the initial and final stages of the growing season, fire activity was to a larger extent disconnected to fire weather index values (IV)

Both tested fire weather index systems were found applicable for the modeling and prediction of the indicators - ignition potential (I), surface fuel moisture (II), or burning coverage (III)- of stand level fire danger but failed to explain the actual fire behavior in terms of rate of spread, flame heights, and fireline intensity (III).

In the estimation of the ignition potential, the Canadian FWI System was significantly better than the FFI (I). The ignition potential formed a strong positive correlation with the FWI code, with correlation coefficient $\rho = 0.93$ ($p < 0.005$) (I) (Fig. 7). Correlation with the FFI was still significant but much weaker, $\rho = 0.59$ ($p < 0.01$) (I). In the fitted linear regressions, the difference increased even further the coefficient of determination (R^2) with the FFI being only 0.34, whereas for the FWI R^2 was 0.87. The FWI explained ignition potential very well in June and July but mostly lost connection with the phenomenon during late season; after July, only a fraction of the ignition potential was observed under fire weather conditions that earlier in the season resulted in 20–80% ignition success (I) (Fig. 8). The overall better performance of the FWI in the assessment of actual ignition and burning conditions was not extremely surprising due to the fact that the FFI has been designed to assess fuel moisture in a relatively deep fuel layer (Heikinheimo et al. 1998, Venäläinen and Heikinheimo 2003) also excluding the direct impact of wind on the burning of fire. The ignition potential formed a better correlation with the FFI when the index was calculated for a 3-cm-thick layer instead of the standard 6 cm (Larjavaara et al. 2004). Splitting the operational FFI system output into 3- and 6-cm components would give more accurate information on surface fire ignition and spread potential even though the index still would not account for the impact of wind speed on fire spread.

The Finnish Fire Risk Index was able to model the average daily moisture content of surface fuels in most stand types with reasonable-to-good accuracy (R^2 : 0.56 - 0.98) (Fig. 8) (II). The regression models determined the ignition threshold moisture content of 30% (I) being reached in *Pinus* clear-cuts at the FFI value of 3.6, and in closed *Pinus sylvestris* stands at the FFI of 5.6 (II) (Fig. 8). For closed *Picea abies* stands, the minimum modeled moisture content for the maximum value of FFI, 6.0, was still above 50% (Fig. 8) (II).

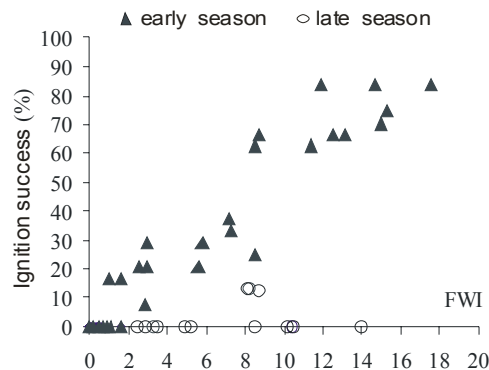


Figure 7. The relationship between daily ignition success percentage and FWI code value during June and July (early season) and August (late season). (I)

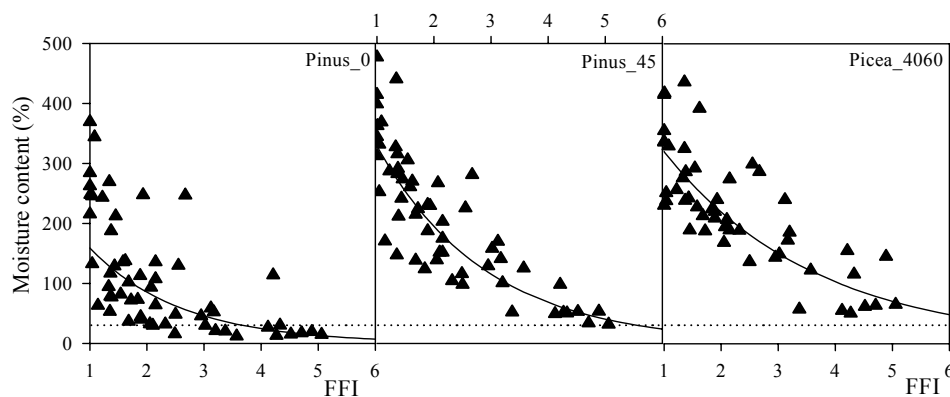


Figure 8. Daily observations of surface fuel MC in relation to index value for the FFI system. Data from three different stand types (Pinus_0, Pinus_45, and pooled Picea_40 and Picea_60). Curves show fitted exponential regressions. The dash lines indicate MC = 30%, a likely limit for fire propagation in these fuels (I). (II)

The FWI explained significantly the extent of burning cover in 15-45-year-old *Pinus* stands, while similar relationship was not found with the FFI (III). In *Pinus* and *Picea* clear-cuts, increase in burning cover showed some correlation with severing fire weather, but presented some fuel material -related limitations (III). In 40-60-year-old *Picea* stands, the tested range of fire weather conditions did not induce any changes into flammability. Neither the FWI System codes nor the FFI correlated significantly with observed spread rates or flame heights, or with the fireline intensity calculated based on fuel consumption (III). The reason for the FWI System failure is likely linked to wind speed observations used for index calculations and actual in-stand wind speeds during experimental fires. Since the experiments were carried out in the midst of forested landscape, and in many cases in-

stand, wind speeds on the plots were likely quite different from regional 10-m wind speed observations. The generally low wind speeds, characteristic to Finnish summer, also resulted in the wind-based FWI System codes to use only a very narrow sector of their full operational range (III).

In the analysis of seasonal fire activity, the relationship between the average observed and modeled fire activity probabilities was generally good (IV). The predicted probability range for all observed fire activity variables remained narrower for the FFI-based models than in the FWI- and ISI-based models (IV), indicating that the latter two indices were better at separating low and high fire danger conditions in relation to the observed fire activity (Andrews et al. 2003). The statistical validity of the FFI-models was, however, slightly better than that of the FWI- and the ISI-models (IV). A proper comparison of the FFI and the FWI System codes was difficult due to different output ranges of these indices which to some extent affected the results of the logistic regression fitting. The FFI has a fixed upper limit (6.0) (Heikinheimo et al. 1998, Venäläinen and Heikinheimo 2003), and its operational range was covered by a reasonable number of observations. The FWI and ISI as open-ended codes (Van Wagner 1987, Stocks et al. 1989) had a few odd observations at very high index values which made forming comparable index range classes challenging. The FFI was able to model fire activity well given that the design of this index reflects fire intensity rather than ignition or fire spread potential. All the indices predicted the highest probabilities of fire-day and multiple-fire-day to occur during the final period of fire season, having the effective temperature sum above 900 d.d. The final stage of the season was, however, also the period when all the models presented the lowest statistical validity (IV). The regression models received the highest pseudo R^2 values and the majority of other best performance indicators during the prime vegetation growth stage, Tsum 50–250 d.d., The assessment of fire danger during the initial and final parts of the growing season, having the highest fine dead fuel loads and the lowest amount of live fuel, could be more accurate using faster reacting fuel moisture codes, such as the FPMC (Martell et al. 1989).

3.5. Structural fire characteristics of managed *Picea abies* and *Pinus sylvestris* stands (I, II, III, IV)

Surface fuel layer was in all stand types predominantly composed of forest mosses. The quality of the moss layer, however, ranged from compact and hardened moss, intertwined with a high amount of litter and slash, in the clear-cuts to spongy, live feather moss layers under closed canopies (I, II, III, Appendix 1). For shrubs and herbs, the maximum layer height was 19 cm and cover 57%, found in 15-year-old *Picea* stands (III, Appendix 1). Fuel load estimations were comparable to the observations of various fuel and biomass studies (Havas and Kubin 1983, Schimmel and Granström 1997). Fuel composition (Appendix 1) generally resembled those observed in *Picea mariana* (black spruce) or *Picea glauca* (white spruce) forests in Alaska (Ottmar and Vihnanek 1998) and *Pinus sylvestris* in northern Sweden (Schimmel and Granström 1997). In these fuel types, live moss and humus are the dominant surface fuel material, and downed woody fuels and shrubs remain a minor fuel component. The main difference to Alaskan coniferous fuel types was the overall shallowness of surface and ground fuel layers (III, Appendix 1).

Stand age appeared to be a major indicator of ignition and fire spread potential in *Pinus sylvestris* stands (I, III, Appendix 1). Clear-cuts had much less moss cover and load than the other stand types and more downed dead woody material (I, II, III, Appendix 1). Many

common boreal forest moss species are known to structurally degrade or even die as a result of canopy removal or the excessive accumulation of litter (Tamm 1953). Nowadays, the detrimental impact of clear-felling on moss layer is additionally enhanced by mechanical site preparation and other use of heavy machinery. The reduction of the quality and cover in moss layer has a significant impact on fire spread because high porosity and surface-to-volume ratio is what makes live boreal forest mosses more efficient fire carriers than needles and coarse woody fuels (Norum 1982, Schimmel and Granström 1997). Approximately after 15 years since clear-cutting or burning, moss layer appears to have recovered enough to again support fire spread (III, Schimmel and Granström 1997). Within the *Pinus* stand structure variation included in this study, the culmination in fire intensity and spread rate occurred in closed semi-mature stands (Appendix 1) that were waiting for their first commercial thinning. In these stands, torching was experienced at maximum by over 60% of stocking (III). Closed, mature *Pinus* stands (Appendix 1), having gone through the first thinning, presented readily spreading surface fires but only marginal torching and crowning (III). In *Picea* stands, general flammability within the tested range of fire weather conditions was so low that stand structure -based differences in fire spread ability could not be properly analyzed. Purely from the stand structure point of view, the occurrence of crown fires would be most likely in *Picea abies* stands (Appendix 1) where the distance between crown and surface fuels remains relatively short (Van Wagner 1977) throughout succession or stands of *Pinus sylvestris* having *Picea abies* understory acting as ladder fuel.

The steadily diminishing average fire size and yearly area burned (Fig. 9) bring up a question whether fire suppression really has become that efficient or if fire danger in this fire environment has decreased for some other reason. In other words, do silviculturally treated, *Picea abies* and *Pinus sylvestris* stands now dominating Finnish forest landscape (Finnish Forest Research Institute 2000) present different fire danger characteristics than the same, native species composition without management? Forest management in Finland has experienced many methodological changes during 20th century and has subsequently changed the forest landscape (Löfman and Kouki 2001). Over 90% of forest area nowadays is managed (Finnish Forest Research Institute 2000). Since 1950s the management has been based on the creation of even-aged stand structures (Löfman and Kouki 2001), and the recommended average rotation time, depending on site productivity and geographical location, has been 60–120 years (Anon. 2001). One of the important landscape-level impacts of commercial forestry comes from limiting the forest age span to cover only the period of active growth (Wallenius 2002) which leads to a nearly complete exclusion of naturally degenerating, and more flammable, stands in the landscape. The elimination of dead fuel accumulation can also be practiced in a smaller scale by removing individual dead standing or downed trees; a practice actively promoted during the latter half of 20th century to improve forest health (Siitonen 2001). At the end of 1990s, the average total volume of standing and downed dead wood in Finnish forests was 1-4 m³ha⁻¹ (Finnish Forest Research Institute 2000), and the lack of dead woody material has been acknowledged as a biodiversity threat for saproxylic species (Siitonen 2001). The reduction of heavy fuels, e.g. as a result of salvage logging, means significantly smaller overall fuel

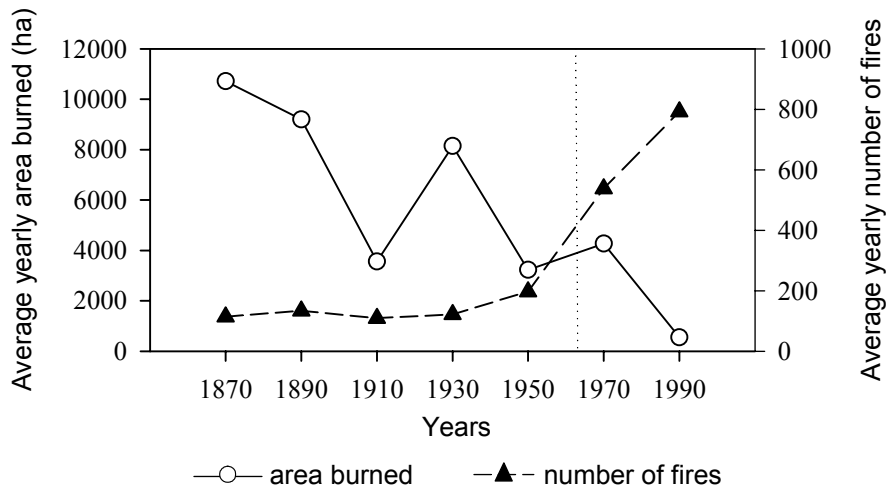


Figure 9. Twenty-year averages of yearly area burned and number of reported fires. Until 1956 (indicated by dash line), values include only state-owned forests (Source: Unpublished fire statistics of Metsähallitus); from 1956 on, values include fires in all forests (Source: the Finnish Ministry of Interior).

loads and reduction in maximum flame lengths and fire intensities (Reinhardt and Ryan 1998). Though some changes have recently been introduced in forestry practices to protect the dead wood dependent species, the load of heavy dead fuels is unlikely to reach levels that would substantially increase fire intensities.

Timber production oriented silviculture involves many stand manipulation methods that resemble actual fuel treatments which aim to eliminate ladder fuels (Graham et al. 2004) and have potential to reduce the probability of extreme fire behavior (Cram et al. 2006) or fire spread in general. These activities consist of the standard timber growth and quality improvement methods, such as clearing of the unwanted understory and thinning and pruning of the dominant tree layer. Additionally, the mechanical site preparation after final cutting not only breaks the horizontal continuum of the moss layer but also further reduces porosity in the remaining moss, already suffered from sun exposure and slash accumulation (Tamm 1953).

A larger scale change, that has been taking place during the past few decades, is the fragmentation of forest landscape due to intensive logging road construction (Uotila and Viitala 2000), and the growing numbers of individual forest owners (Karppinen et al. 2000). Logging roads act as firebreaks and provide easy access to detected fires in sparsely inhabited areas that previously would have been difficult targets for fire suppression. The average size of a forest compartment, i.e. forest management unit of homogeneous structure, is currently less than two hectares, and the average size of a private forest holding ranges from 20 to 30 ha (Karppinen et al. 2000). Decreasing forest compartment size creates more complexity in the landscape. In terms of fire danger, the increasing forest landscape heterogeneity means less straight fire travel route patterns and reduced fire growth potential (Finney 2003) because more flammable stand types are more likely to be interrupted by those who act as fire barriers. Under extreme fire weather conditions, high

landscape heterogeneity, on the other hand, may increase the difficulty of fire behavior prediction.

4 CONCLUSIONS

The findings of this study suggest that the dominance of *Picea abies* or *Pinus sylvestris* and stand age have a remarkable impact on surface ignition potential, fuel moisture and fire behavior and that taking these differences into account in weather-based fire danger prediction would benefit fire management operations.

Both the Canadian Fire Weather Index (Van Wagner 1987, Stocks et al. 1989) and Finnish Fire Risk Index (Heikinheimo et al. 1998, Venäläinen and Heikinheimo 2003) show potential for the evaluation of stand-specific burning conditions. The FWI includes components for assessing both fuel moisture and fire behavior. The currently operationally used FFI can be adapted to estimate local fuel moisture and the amount of available fuel, but the system does not currently provide means for the prediction of actual fire behavior.

Seasonal changes in fire danger would require a more extensive approach than this study was able to provide. The weakening impact of seasonal progress on fire danger was, however, consistent in our field experiments and in the national fire records. Due to strong human influence, ignition sources are plenty throughout the season, but the stage presenting the highest fire spread potential appears to take place in May and early June. In addition to the actual flammability of the landscape, seasonal stage affects the ability of fire weather indices to assess fire danger accurately. The slower reacting indices, such as the FFI, FWI, and ISI, perform most reliably during mid-season, i.e. the period having the highest live surface fuel proportion. During the initial and final stages of the fire season, attention should be paid to local fuel composition and field observations on fuel moisture to accurately assess burning conditions.

Commercial forestry presumably modifies fire regimes because fuel types resulting from long-term forest management are quite different from an unmanaged setting, e.g. lacking multi-layered canopies, old-growth stands, and downed coarse woody debris. Extensively applied, unintentional fuels management can have a particularly powerful, diminishing impact on fires in a fire environment such as Finland where fire weather and topography mostly lack features that could contribute to extreme fire danger.

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APPENDIX 1.

Observations on fuel conditions and fire behavior in *Picea abies* and *Pinus sylvestris* stands

Naming: The short name of a fuel type (e.g. Pinus_0) indicates dominant tree species and the age of stand. The long name consists of the full name of the dominant tree species (*Pinus sylvestris* / *Picea abies*), the approximate developmental phase of a stand, the level of canopy closure (open / closed), and the site type (VT: *Vaccinium vitis-idaea* -type, MT: *V. myrtillus* -type, according to Cajander 1926).

Photos: A general outlook of a fuel type with a fuel height marker pole (total height = 1.5 m) and a close-up of the surface fuel layer (50 cm × 50 cm area).

Description: A brief general description of the fuel composition, typical fire behavior, and factors affecting fire danger.

Table “Fuel properties”: Description of total fuel loads in the following fuel layers: trees (dm ≥ 5cm, H ≥ 4 m), saplings (dm < 5 cm, H < 4m), herbaceous or shrub vegetation (depending on which one is dominant), downed dead woody fuel (all dimensions combined), and moss layer including upper live moss part intermingled with fine litter and the lower dead moss layer.

Table “Fire characteristics”: Summary of the observations in the field burning experiments (study III). Reference row (1st): the LST noon value of the FWI code of the Canadian FWI System. Other rows: the noon value of the FFI, sampled moisture content (MC) in the upper moss layer, the average speed of mid-flame downwind (m s⁻¹), fire front's average rate of spread (ROS) (m min⁻¹), flame height (Flame H) (m), and fireline intensity (I), calculated based on the rate of spread and fuel consumption in surface fuel layer.

List of the described fuel types:

Pinus_0 = *Pinus sylvestris* clearcut (VT)

Pinus_15 = *Pinus sylvestris* open, immature stand (VT)

Pinus_30 = *Pinus sylvestris* closed, semi-mature stand (VT)

Pinus_45 = *Pinus sylvestris* closed, mature stand (VT)

Picea_0 = *Picea abies* clearcut (MT)

Picea_15 = *Picea abies* open, immature stand (MT)

Picea_4060 = *Picea abies* closed, semi-mature or mature stand (MT)

Pinus_0*Pinus sylvestris* clear-cut (VT)

Description: Surface fuel material consisted of 2–8 cm deep layer of moss and humus (to some extent compacted), logging slash, and live herbaceous and shrub vegetation. Fire spread was slow-to-moderate; intensities varied from low to high depending on the spatial arrangement and composition of fuels resulting from logging and site preparation activities.

Table: Fuel properties

	Stems/cover (N/ha) (%)	Height (m)	Load (t/ha)
Trees	70-120	21-30	20-41
Saplings	3000-9000	0.3-0.8	0.02-0.05
Herbs			
Shrubs	4-41 (%)	0.08-0.14	0.1-1.1
D woody	-	-	1.5-2.6
Moss	6-85 (%)	0.02-0.08	3.8-10.6

Table: Fire characteristics

FWI	7	11	14
FFI	3	2	4
Fuel MC (%)	25	11	11
Wind (m s⁻¹)	1.6	1.1	0
ROS (m min⁻¹)	0.6*	0.5*	0.5*
Flame H (m)	0.9	0.3	0.4
Fireline I (kW m⁻¹)	20	0	190

*Incomplete plot burn.

Pinus_15*Pinus sylvestris* open, immature stand (VT)

Description: Surface fuel material consisted of 3-8 cm of moss, humus, and decomposing litter, a minor amount of logging slash, dwarf shrubs (mainly *Vaccinium vitis-idaea* and *Calluna vulgaris*), and understorey saplings (*Pinus sylvestris*, *Picea abies*, deciduous trees). Moss layer was shallow and to some extent compacted. Tree crowns extended close to the ground and facilitated torching. Fire spread was moderate; and flame heights varied from 10 cm to a few meters in the occasion of torching.

Table: Fuel properties

	Stems/cover (N/ha) (%)	Height (m)	Load (t/ha)
Trees	500-1700	4.3-6.7	2.4-13.2
Saplings	6500-27000	1.3	0.6-2.5
Herbs			
Shrubs	29-49 (%)	0.11-0.19	0.8-1.3
D woody	-	-	1.5-2.7
Moss	62-89 (%)	0.03-0.08	2.6-10.9

Table: Fire characteristics

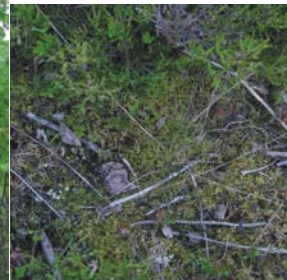
FWI	11	14	17	20
FFI	2.8	3.8	4.2	4.4
Fuel MC (%)	-	26	13	14
Wind (m s⁻¹)	0.1	0.8	0.3	0
ROS (m min⁻¹)	0.8	1.4	0.4	0.3
Flame H (m)	0.5	0.8	0.6	0.4
Fireline I (kW m⁻¹)	200	310	160	20

Pinus_0

Pinus sylvestris clear-cut (VT)

**Pinus_15**

Immature *Pinus sylvestris* stand (VT)



Pinus_30

Closed immature *Pinus sylvestris* (VT)

**Pinus_45**

Closed, mature *Pinus sylvestris* stand (VT)



Pinus_30*Pinus sylvestris* closed, semi-mature stand (VT)

Description: Surface fuel material consisted of 9-10 cm of moss, humus, and decomposing litter, dwarf shrubs (*Vaccinium vitis-idaea*), and understorey saplings (*Pinus sylvestris*, *Picea abies*, deciduous trees). The lower dead branches of the dominant trees extended close to the surface fuel layer and facilitated torching. The dense spacing of dominant trees contributed to high fire intensities and briefly supported crown fire. Fire spread ranged from moderate to fast; fire intensities from moderate to high.

Table: Fuel properties

	Stems/cover (N/ha) (%)	Height (m)	Load (t/ha)
Trees	1800-2200	9-15	36-87
Saplings	2500-9800	0.8	0.04-0.14
Herbs			
Shrubs	23-30 (%)	0.10-0.12	0.6-0.8
D woody	Na	na	1.0-1.6
Moss	95-99 (%)	0.09-0.10	7.9-9.7

Table: Fire characteristics

FWI	14	17	20
FFI	3.8	4.6	4.6
Fuel MC (%)	11	11	7
Wind (m s⁻¹)	0.2	0.7	0
ROS (m min⁻¹)	1.1	3.4	0.8
Flame H (m)	0.9	3.4	0.8
Fireline I (kW m⁻¹)	340	1400	320

Pinus_45*Pinus sylvestris* closed, mature stand (VT)

Description: Surface fuel material consisted of 5-11 cm of moss, humus, and decomposing litter, dwarf shrubs (*Vaccinium vitis-idaea*), and understorey saplings (*Pinus sylvestris*, *Picea abies*, deciduous trees). Fire spread ranged from slow to fast; flame heights from low to moderate.

Table: Fuel properties

	Stems/cover (N/ha) (%)	Height (m)	Load (t/ha)
Trees	700-1100	11-19	41-98
Saplings	1600-10000	0.8	0.02-0.14
Herbs			
Shrubs	29-48 (%)	0.09-0.15	0.8-1.3
D woody	n/a	n/a	0.8-0.9
Moss	76-100 (%)	0.05-0.11	3.6-13.1

Table: Fire characteristics

FWI	3	7	10	11	14	15	17	20
FFI	3.5	3.3	3.1	2.8	3.8	4.6	4.4	4.4
Fuel MC (%)	64	80	17	13	13	13	17	15
Wind (m s ⁻¹)	0	0	0.1	1.5	0.9	0.2	0.8	1.1
ROS (m min ⁻¹)	0.1*	0*	0.1*	3.0	1.2	0.7	1.4	1.9
Flame H (m)	0.3*	0.2*	0.2*	0.6	0.7	0.5	1.3	1.7
Fireline I (kW m ⁻¹)	10*	0*	30*	820	360	300	270	300

*The plot remained partially unburned.

Picea_0

Picea abies clear-cut (MT)

**Picea_15**

Open, immature *Picea abies* stand (MT)



Picea_4060

Closed, 40-60-year-old *Picea abies* stand (MT)



Picea_0*Picea abies* clear-cut (MT)

Description: Surface fuel material consisted of 2-4 cm deep layer of moss and humus (in part compacted), patches of logging slash, and live herbaceous vegetation. Fire spread rates were low. Fireline intensities varied from low to high being strongly modified by the spatial arrangement and composition of fuels as a result of logging activities. Fire potential was diminished by seasonal growth of herbaceous vegetation.

Table: Fuel properties

	Stems/cover (N/ha) (%)	Height (m)	Load (t/ha)
Trees	0	0	0
Saplings	5000-26000	0.1-0.4	0.01-0.07
Herbs	27-42 %	0.10-0.15	0.1-0.2
Shrubs			
D woody	Na	na	2.3-3.2
Moss	6-65 (%)	0.02-0.04	0.7-7.9

Table: Fire characteristics

FWI	10	15	17	20
FFI	3.5	4.4	4.2	4.6
Fuel MC (%)	87		14	10
Wind (m s⁻¹)	0.3	0.4	0.5	1.3
ROS (m min⁻¹)	0*	0.1*	0.3*	1.0
Flame H (m)	0	0.5	0.3	0.8
Fireline I (kW m⁻¹)	0			200

*The plot remained partially unburned.

Picea_15*Picea abies* open, immature stand (MT)

Description: Surface fuel material consisted of 3-4 cm of moss, humus, and decomposing litter and live herbaceous vegetation. Spread rates, fire intensities, and a general flammability were very low, presumably due to the high amount green grass versus the low amount of somewhat compact moss. Tree crowns extended to the ground and supported occasional torching. The highest fire potential can be assumed to occur when grasses are cured, i.e. early spring before the growth starts or late autumn.

Table: Fuel properties

	Stems/cover (N/ha)(%)	Height (m)	Load (t/ha)
Trees	300-1600	5-7	1-11
Saplings	16000-27000	0.8-1.3	0.2-0.4
Herbs	35-80 %	0.17-0.22	0.2-0.4
Shrubs			
D woody	Na	na	na
Moss	32-44 (%)	0.03-0.04	1.2-2.3

Table: Fire characteristics

FWI	8	10	20
FFI	3.6	3.5	4.4
Fuel MC (%)		57	45
Wind (m s⁻¹)	0	0.3	0
ROS (m min⁻¹)	0	0	0.7
Flame H (m)	0	0	0.6
Fireline I (kW m⁻¹)	0	0	65

Picea_4060*Picea abies* closed, mature stand (MT)

Description: Surface fuel material consisted of 4-12 cm of moss, humus, and decomposing litter plus dwarf shrubs (*Vaccinium myrtillus*). Fire spread and fireline intensities were close to zero. Under more extreme fire weather conditions, stands may have potential for crown fire due to low-reaching canopies that contain dead branch material.

Table: Fuel properties

	Stems/cover (N/ha) (%)	Height (m)	Load (t/ha)
Trees	600-1300	15-24	73-121
Saplings	100-13000	0.3-0.8	0.00-0.12
Herbs	11-49 (%)	0.09-0.11	0.1-0.3
Shrubs			
D woody	-	-	1.5-2.6
Moss	63-98 (%)	0.04-0.05	2.7-14.7

Table: Fire characteristics

FWI	3	11	15	17	18	20
FFI	3.5	4.0	4.4	4.6	5.0	4.6
Fuel MC (%)	94	19		76		11
Wind (m s⁻¹)	0	0.	0	0.1		0.4
ROS (m min⁻¹)	0	0.2*	0	0	0	0
Flame H (m)	0	0.6*	0	0	0	0
Fireline I (kW m⁻¹)	0		0	0	0	0

*The plot remained mostly unburned.